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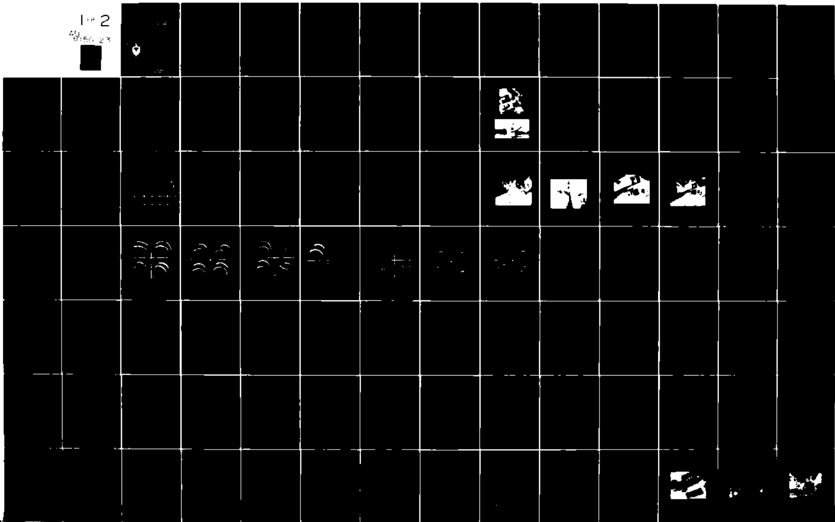

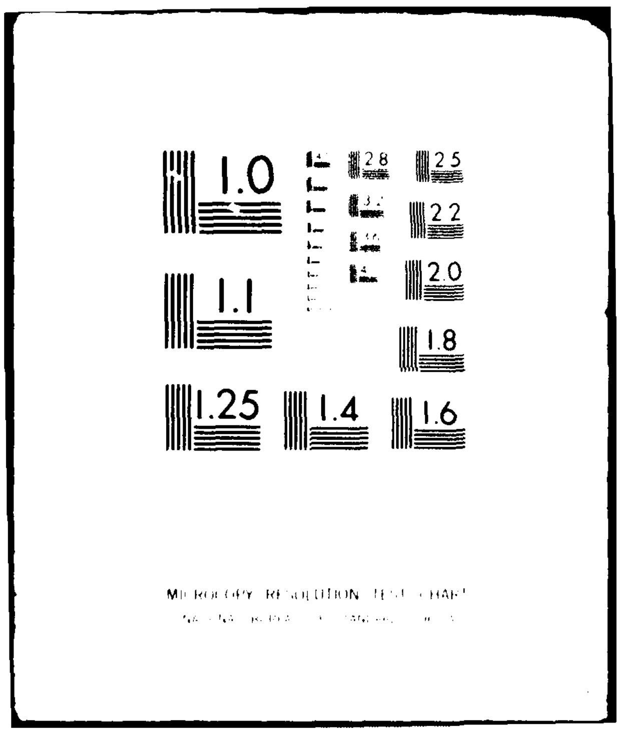
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FLO-PEELING AND OTHER ALTERNATIVES TO CONVENTIONAL TURNING

O.D. LASCOE, J.I. EIGOMAYEL and C.W. REZEK
PURDUE RESEARCH FOUNDATION

and

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OCTOBER 1977

TECHNICAL REPORT

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4. Rotary Grinding
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6. Multiple-head
7. Single-edge
8. Multiple-tooth
9. Self-propelled
10. Power-driven

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Machining of 4140 alloy by flo-peeling, and by related turning, milling and grinding was evaluated using self-propelled and power-driven, single-edge and multiple-edge, cutting tools. The cutting tools included HSS (high-speed-steel) and carbide discs, HSS and carbide milling cutters, and abrasive grinding wheels. Tests were conducted using 15 HP and 20 HP lathes with a single cutter head mounted on the lathe cross-slide, and with a multiple-head assembly mounted on the carriage. Test variables also included combinations of cutter positions and

291 600

20. ABSTRACT (continued)

other machining parameters; viz., tool geometry, speed, feed, depth of cut and coolant. Primary testing was by turning with rotary discs in the following ranges: speed - 30 SFPM to 1000 SFPM, feed - .0102 IPR to .073 IPR, depth - .007 in. to .061 in. A cutting efficiency of 1.65 in.^{3}/min/HP was reached using a single, self-propelled, HSS disc at .0166 IPR, 300 SFPM, and .0185 in. depth; and a 20-25 RMS surface finish was obtained using two HSS discs at .0166 IPR, 1000 SFPM, and .035 in. depth. Power required ranged from 0.606 HP to 17.3 HP; but, the metal-removal rate, efficiency, and quality of surface finish were limited by torque, vibrations, and chatter. Various longitudinal and radial spacings of multiple cutters were tried to reduce vibrations, but chatter remained problematic.

The tests with power-driven milling cutters and abrasive wheels showed less efficiency, and yielded rougher surfaces than the cutting with discs. (U) (Lascoe, O.D., ElGomayel, J.I., Rezek, C.W., and Kirschbaum, R.A.)

FOREWORD

This report was prepared by O. D. Lascoe, J. I. ElGomayel, C. W. Rezek of the Purdue Research Foundation, West Lafayette, Indiana 47907, in compliance with contract DAAF03-73-C-0012, and by R. A. Kirschbaum, Engineering Directorate, Rock Island Arsenal, Rock Island, IL 61201.

This work was authorized as part of the Manufacturing Methods and Technology Program of the US Army Materiel Development and Readiness Command, and was administered by the US Army Industrial Base Engineering Activity.

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INTRODUCTION

The evaluation of flo-peeling and related rotary-cutting mechanisms was initiated to overcome the mechanical deficiencies and limitations of single-point turning. As basic machining mechanisms for shaping and finishing cylindrical workpieces, the conventional single-point tool and lathe are inherently limited. Performance of the single-point tool, in normal wear, is limited by the high mechanical and thermal stresses and shocks to which it is continuously and intermittently subjected, in a concentrated area. The lathe is generally a structure having a tool-post, tailstock, headstock, power-train and feed screw which are cantilevered, offset, from its frame. In combination, the single-point tool and the lathe -- tool-post, headstock-chuck, tailstock-center -- subject the workpiece to dynamic bending forces, as applied to a simple rotating-beam, which inherently cause vibrations.

In contrast, the flo-peeling, rotary-turning mechanisms and cutting-tools can be arranged about the workpiece to avoid cantilevering of machine tool elements, to subject the rotating workpiece to compressive stresses instead of tensile stresses from bending, to allow simultaneous cutting of multiple tools, and to avoid the normal wear which requires frequent and costly changing of single-point turning tools. Furthermore, development of rotary-tool turning has shown, not only the potential of improving turning machines, but also, the feasibility of eliminating regular tool changing, by grinding and/or spray coating the rotary tool while cutting.

The "Flo-Peel" Process has been under investigation for the past thirty years. A specially designed vertical Flo-Peel Machine was built by Lodge and Shipley Machine Tool Company, Cincinnati, Ohio to prepare large billets for extrusion. The Lodge & Shipley concept was developed from their Floturn Machine in which metal deformation is caused by a spinning and drawing action. Flo-Peeling involves point deformation of the material, exceeding the yield point of the material so that it shears and flows as directed by the circular disc shape.

The state of the art of shearing and peeling goes back to the skill of the pattern or wood worker using a skew wood chisel to turn a cylindrical wood part, thereby resulting in a true shear cut that produced, especially on hard wood, a superior finish.

Among the many tools researched and used for metal cutting operations, the rotary turning disc is a concept that has been under study by researchers in Japan, Germany, Russia, and the U.S.A. for the purpose of compiling machinability data for turning operations. This concept was expected to reduce cutting tool temperature and tool wear when compared with conventional single point tools. Most of the investigations conducted by these groups centered around a single self-propelled rotary disc for a straight turning operation.

The surveys of published technical papers reveal some interesting comments and results as to the state of-the-art related to the disc-turning concept. Shaw, Smith, and Cook[1] analyzed 12 rotary turning tools indicating that the results of their test decreased the cutting forces on the tool by 30% and a drop in cutting temperature of approximately 220°C. Standinger[2] in Germany stated that the advantage of the rotary turning tool is the small tool wear and the high surface finish obtained when turning rotors for electric motors and the cutting speed and feed can be increased compared to conventional systems. In USSR, Zemlyanskii[3,4] and co-workers investigated mainly the theory of the stationary rotary turning tool with its kinematics and wear relationship. Japanese researchers Kasei and Hara[5] investigated a rotary cutting tool in the form of a frustum of a cone that rotated around its central axis and was self-propelled. The crater characteristics and flank wear were theoretically analyzed and compared with that of a conventional cutting tool. Other investigators[6,7,8] showed by tests made in a shop environment (turning of castings and titanium alloys), a 40% increase in tool life when using constant cutting conditions or a 2 - 5 times higher

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1 M. Shaw et al., "The Rotary Cutting Tool," Transactions of the ASME, August 1952, p. 1065-1076.

2 H. Standinger, "The Use of Rotary Tools for Machining Parts for the Electro Industry," Z-VDI 104 (1962) 19, p. 867-870.

3 V.A. Zemlyanskii et al., "Upon the Kinematics of Self Propelled Rotary Discs," Somoletostroenie i technika Vozdusnogo flota (1965) 1, p. 112-119.

4 V.A. Zemlyanskii et al, "Machining Titanium Alloys Using Rotary Discs," Stanki i reznscie instrumenty 8 (1968), p. 70-75.

5 S. Kasei, T. Hara, "Researches on Turning with Self Propelled Rotary Cutting Tool," Journal of the Japan Society of Precision Engineering. Vol. 35, No. 10 (1969) p. 656, Vol. 37, No. 4 (1971) p. 239, Vol. 37 No. 10 (1971) p. 723 and Vol. 37, No. 12 (1971) p. 855.

6 B.S. Derganov, "Rotary Disc Cutting Tool," Masinostroitel (1966),10, p. 37, S.A.: VDMA-P4414-218.91.

7 E.G. Kanovalov, "The Use of Rotary Cutting Tools in Order to Increase the Efficiency in Cutting Operations," Vestnik Nasinostroenija 49 (1969) 8S.66.

8 K. Tollner, "Untersuchungen Mit Drehwerkzeugen Mit Umlaufender Schneidscheibe," Dr. Eng. Dissertation, Technical Univ. of Aachen, Germany, June 1971.

cutting speed when the tool life factor was constant. Eskelin[9] and Vaughn[10] describe cutting tests using milling cutters with rotating cutting edges to machine titanium. Results indicate a 2 - 4 times higher cutting speed and better surface finishes compared with conventional milling cutters.

These investigations provide an insight into the degree of interest in analyzing the use of rotary disc cutters for turning operations. The publications, surveyed in this work (see Bibliography), cover specific applications using rotary discs for turning operations under different cutting conditions. The results can be valid only within narrow limits. From these reports, the following are key points worthy of consideration:

1. Most of the investigations involved single rotary disc cutters positioned in front of the workpiece and positioned in two axis, except the Lodge and Shipley flo-peeling system.

2. Improved surface finishes were obtained, even at lower cutting speeds.

3. The temperature differential of heating and cooling is increased due to the cutting edge rotation. The maximum temperature of the rotating tool is much lower than that of the fixed single point tool.

4. The wear rate of the rotary cutting tool was very small and the tool life increased when compared to single point tools.

5. The friction velocity between the rake face and the chip decreased since the chip flows toward the rotated direction of the cutting edge.

6. Cutting with a rotary tool produced a relief angle different than the tool's own relief angle.

7. The larger the angle of inclination, the smaller the working relief angle will be; therefore, the flank wear width will be larger.

8. In the Klaus Tollner research, the main variables measured were stresses and friction on the bearings of a free wheeling rotary tool, made from several High Speed Steel (HSS) grades. The rotary tool performance was reported to be 10% to 30% better than single point tool. For the same surface requirements a rotary tool may be used at higher feed rates and cutting speeds removing more cubic inches of metal. Rotary tool's best application was for long, large diameter bars with no interrupted cuts. Cost analysis proved their superiority over single point tools.

---

[9] A.F.Eskelin, "Rotating Carbide Inserts Machine Titanium Faster," Machinery 73 (1966) 4, p. 96-98.

[10] R. L. Vaughn, "Faster Machining of Titanium," American Machinist 112 (1968) 10, p. 98-99.

PRELIMINARY INVESTIGATIONS

In the first phase of the research project, data was obtained on the self-propelled rotary disc cutter and the power-driven cutter. Positioning of the disc cutter with respect to the workpiece was studied in more detail to acquire information on the peeling effect in the metal cutting operation. Several bar stocks of Kirksite material and aluminum were cast for preliminary testing since the materials are easily machined.

It was anticipated that numerous test runs should be conducted to obtain reliable information on the rotary disc set-up; and an original statistical experimental design was developed with a complete factorial where seven independent variables were considered at several levels of each. These seven variables and their levels were chosen as follows:

1. Disc Drive at three levels: free, clockwise power-driven, counter-clockwise power-driven.

2. Disc Design at three levels: Figure 1 shows a blank rotary disc while Figures 2, 3, and 4 show the three different cutting edges on the cutting discs.

3. Workpiece Material at three levels: Kirksite, aluminum (which were specially cast for this project) and leaded, free-machining steel bars.

4. Disc Positioning - In the geometry of the disc set-up with respect to the workpiece (which is illustrated in Figure 5), the angles α and β were chosen as the main parameters to identify the positioning of the rotary disc. Six combinations of these two angles were decided upon as the six levels of this independent variable. The combinations were as follows:

α	β
15°	0°
15°	15°
15°	30°
30°	0°
30°	15°
30°	30°

5. Cutting Speed at two levels: 150 and 250 surface feet per minute (SFPM).

6. Feed Rate at two levels: Manual and automatic.

7. Depth of Cut at two levels: Light and Heavy depths of cut.

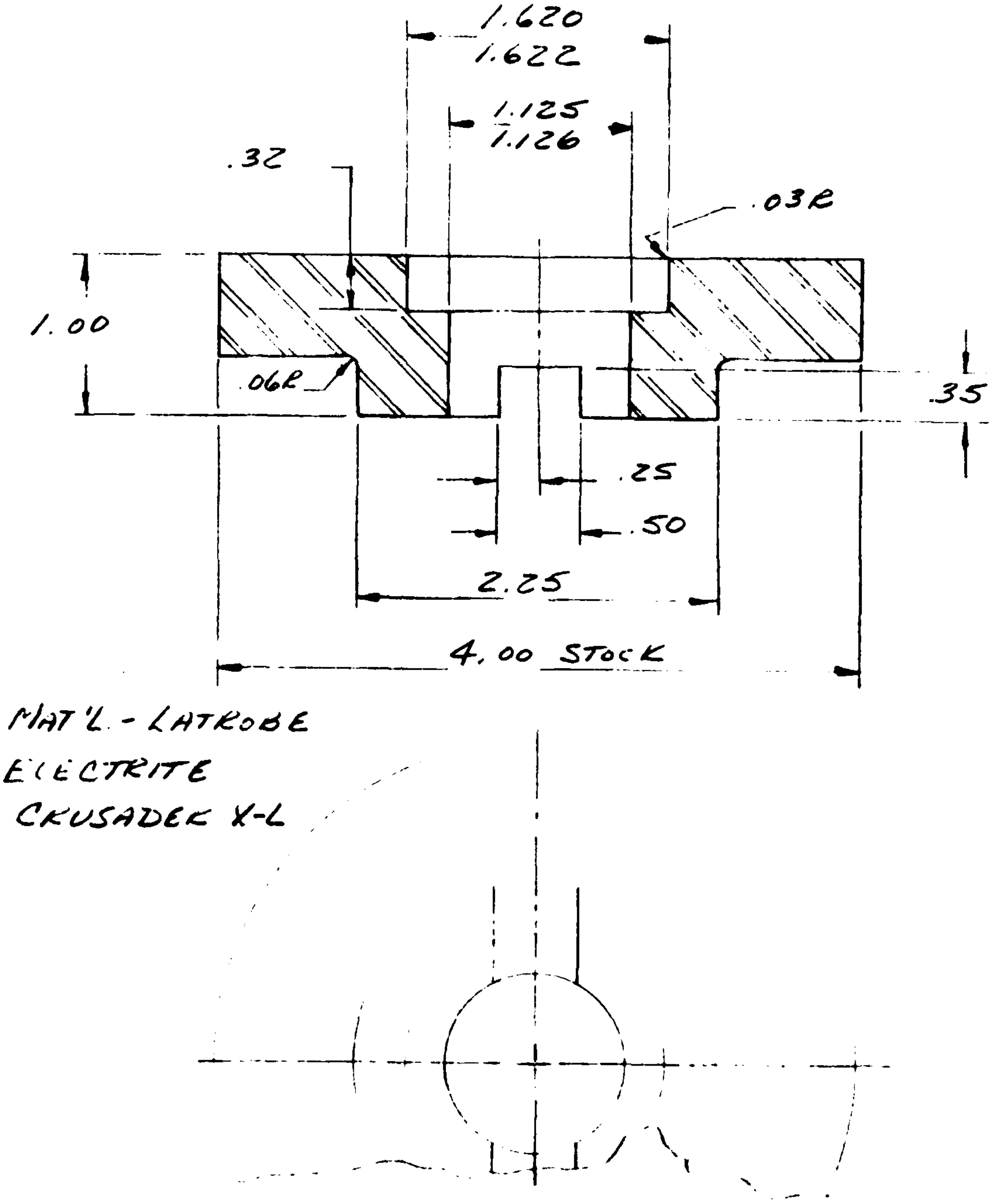
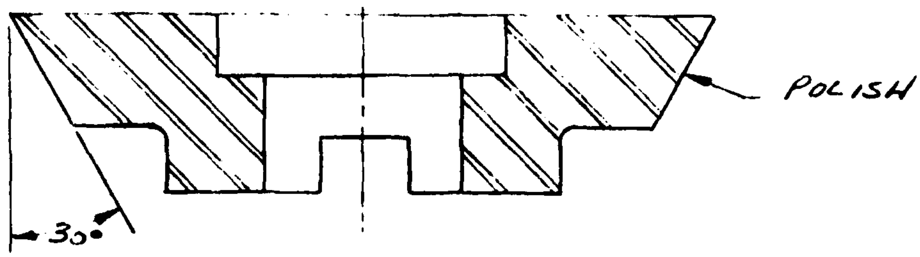


FIGURE 1. Rotary Cutter Blank



NOTE:
MATERIAL - LATROBE ELECTRITE CRUSADER-XL
HARDEN & DRAW TO ROCKWELL C-66

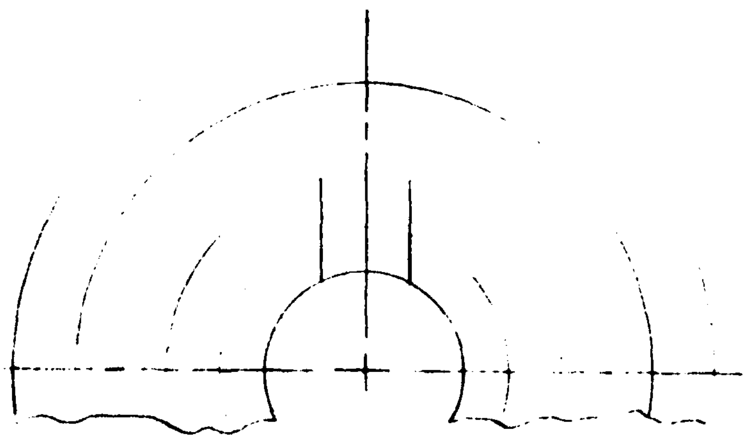
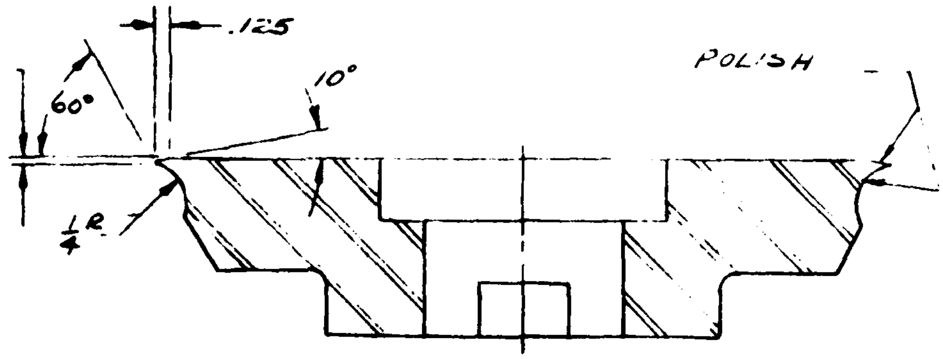


FIGURE 2. Cutter for Globe Mill - #1



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HARDEN & DRAW TO ROCKWELL C-66

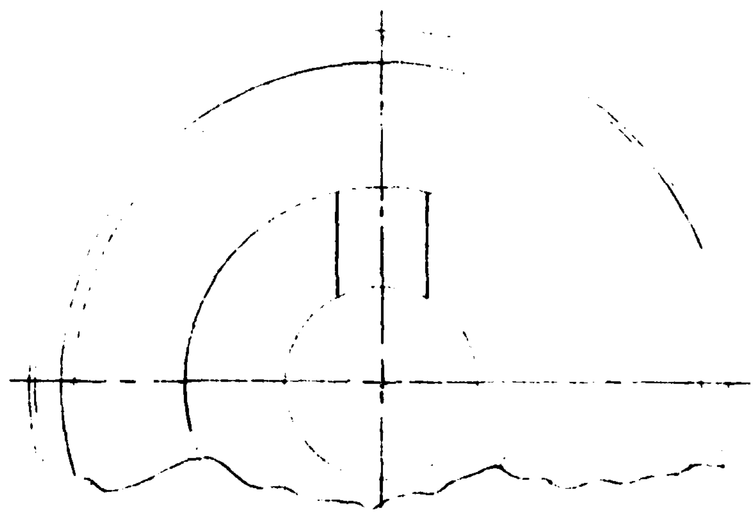

FIGURE 3. Cutter for Globe Mill - #2

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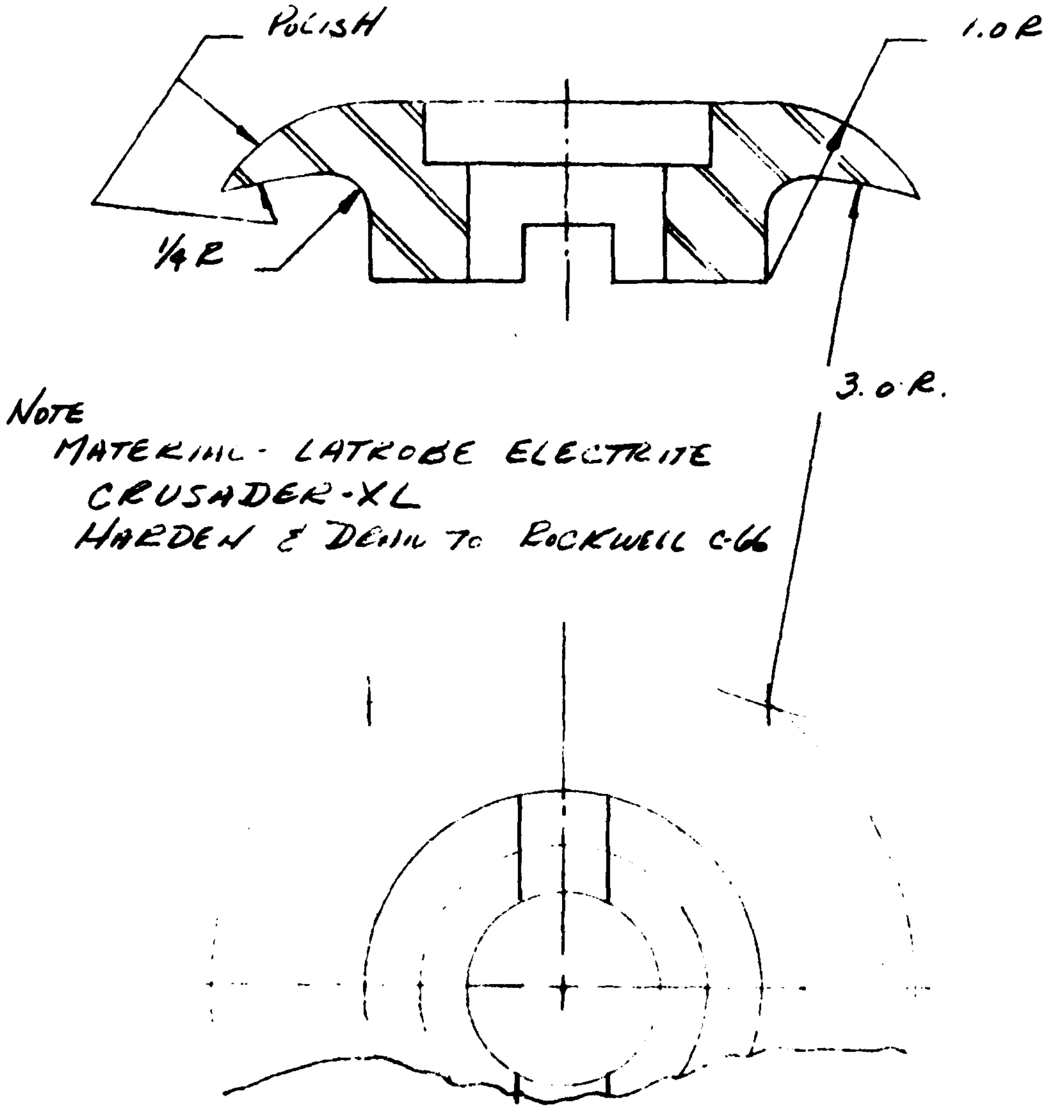


FIGURE 4. Cutter for Globe Mill - #3

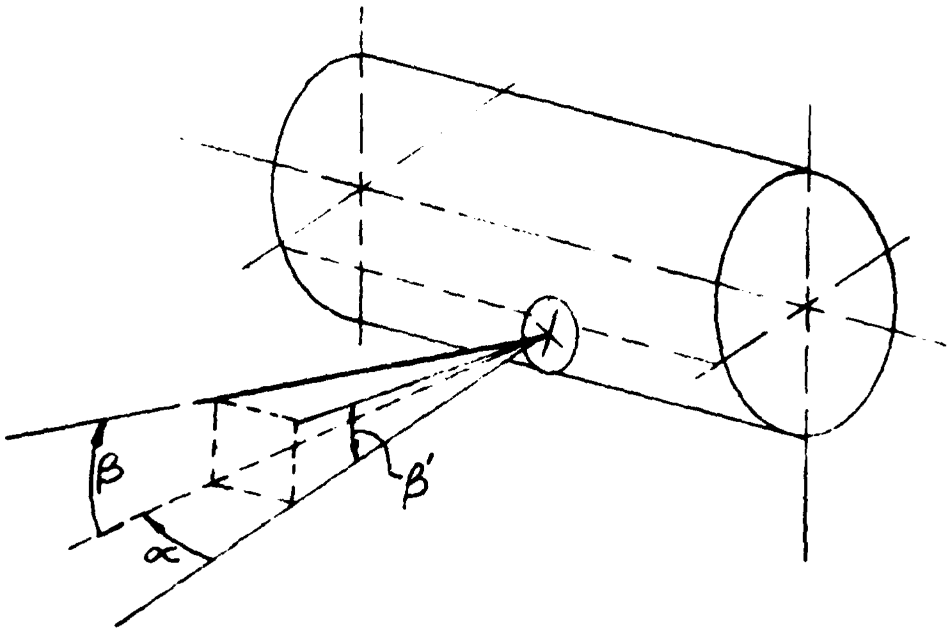


FIGURE 5. Cutting Tool Angles

To test all these variables with their chosen level a complete factorial design required $3^3.6^1.32 = 5184$ treatment combinations. However, only eleven tests on the Kirksite material and fifteen tests on the aluminum were conducted. The data obtained from these chosen tests were conclusive enough to decide on dropping the balance of the treatment combinations and proceed to the main phase of the project.

The results of these test runs can be summarized as follows:

A. <u>Kirksite as the work material</u>. A power-driven disc with a preferred relative movement (disc clockwise, workpiece clockwise) exhibited the best peeling results; the cutting parameters were as follows:

Disc position; $\alpha = 15^\circ$, $\beta = 0^\circ$

Cutting speed = 250 SFPM

Workpiece diameter = 4.5 in.

Depth of cut = .030 in.

Feed Rate = .012 in./rev.

The original power drive was a commercially-available Globe milling head attachment driven by a one HP electric motor. Figure 6 shows the picture taken during the machining of the Kirksite work material. While machining the same work material, acceptable cuts were obtained when $\beta = 15^\circ$; but with large β angles the following cutting parameters started to deteriorate. It was also concluded that a power-driven disc would cut more effectively in the Kirksite than a free-wheeling tool.

B. <u>Aluminum as the workpiece material</u>. Best results were obtained with free-wheeling disc (where the peeling was very noticeable) at the following parameters:

Disc position: $\alpha = 15^\circ$, $\beta = 0^\circ$

Workpiece diameter = 2.5 in.

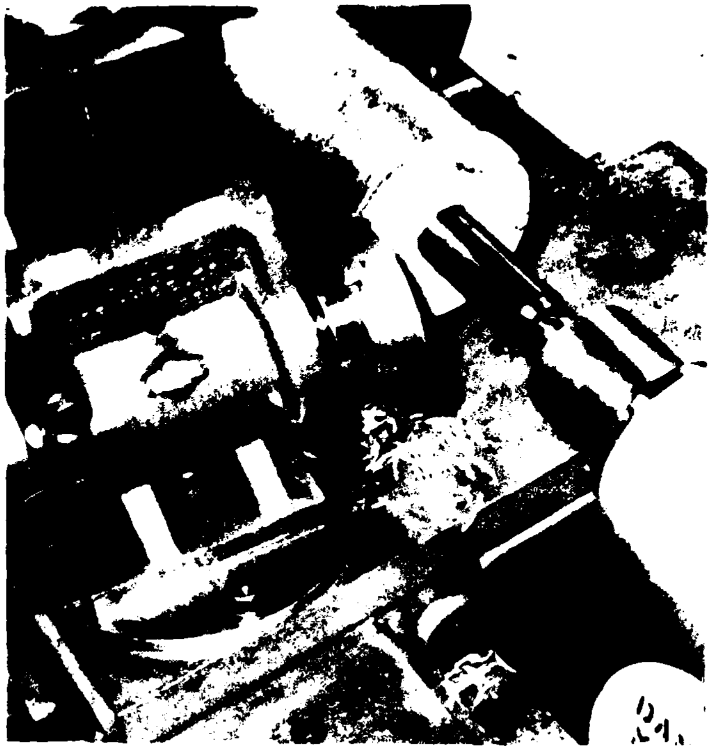
Cutting speed = 170 SFPM

Depth of cut = .080 in.

Feed = .012 in./rev.

Powering the rotary disc resulted in a failure (the disc reversed directions and lacked driving power).

These preliminary tests provided some useful design data that were essential for positioning the disc and its holder. The set-up for the rotary disc must provide the following:



Self-propelled & Power Driven

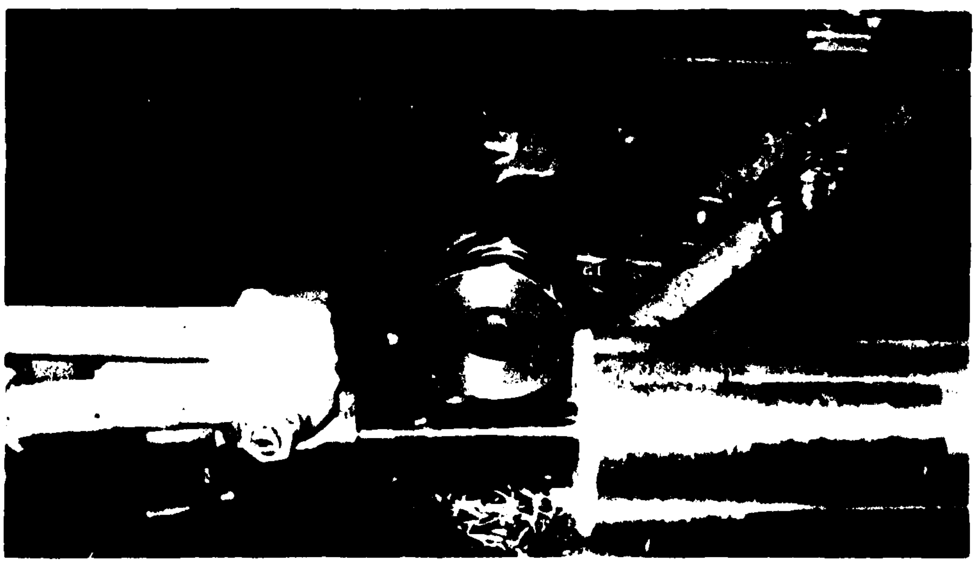


FIGURE 6 Cast Kirksite Log Set-up - 4" HSS Cutter

1. Rotation of the cutting axis at any chosen speed under its own separate power source.

2. Independent angular adjustment of α and β.

3. Vertical height adjustment (relative to the workpiece).

4. Radial depth of cut adjustment (relative to the workpiece).

5. Horizontal axial feed rates (relative to the workpiece).

Since the tool holder is to be mounted on a lathe compound, movements 4 and 5 should come from the motion of the carriage compound on the lathe.

A part of the preliminary testing included the fabrication of a mandrel to be set in the Globe milling head accessory (Figure 7 shows the mandrel and the rotary disc). The mandrel and the rotary disc had a vertical height adjustment capability. This device was mounted on the lathe compound such that the angle α was adjustable. The adjustment of the angle β' was provided by a combination of vertical and radial movements of the disc relative to the workpiece. A powered mandrel was fabricated with a vertical height adjustment capability (See Figure 2). This device was mounted on the lathe compound such that the angle α was adjustable. The equivalent adjustment of the angle β' was provided by a combination of vertical and radial movements of the tool relative to the work.

The following equations were developed to approximate the Vertical (V) and Horizontal (H) movements of the tool relative to the workpiece to simulate a relative tool angle. These geometries are described below:

(1) $\tan\beta = \cos\alpha \tan\beta'$

(2) $V \simeq r \sin\alpha \tan\beta' \sqrt{\dfrac{1}{1 + \sin^2\alpha \tan^2\beta'}} + R\sin\beta'$

(3) $H \simeq R(1 - \cos\beta') + r\sin\alpha \left[1 - \sqrt{\dfrac{1}{1 + \sin^2\alpha \tan\beta'}}\right]$

Equations 2 and 3 were used as follows:

a. Tool radius r and workpiece radius R were determined.

b. Angles α and β were selected.

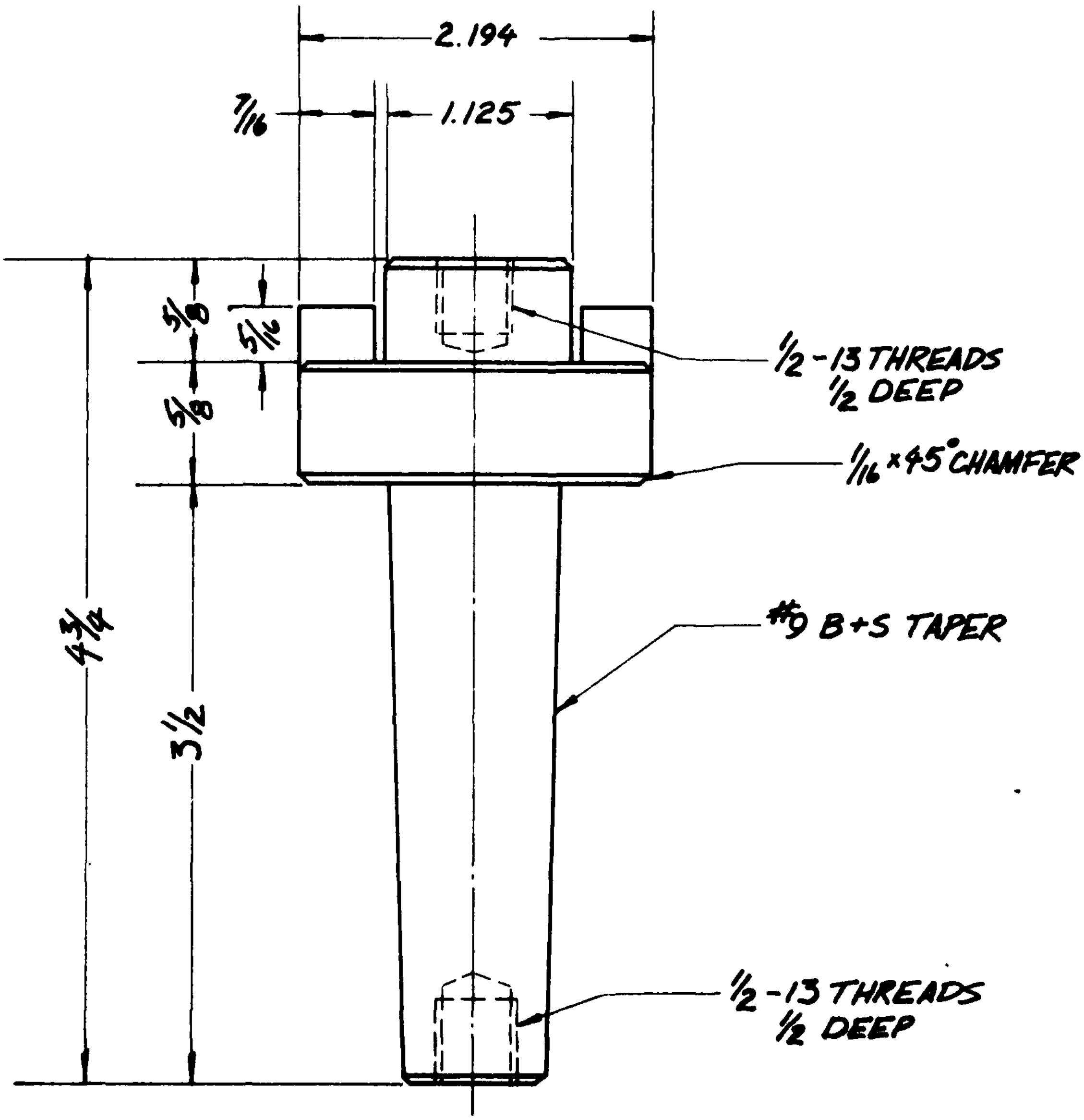


FIGURE 7 Cutter Mandrel

c. V and H were computed. (A computer program was developed to generate tables as functions of α and β).

d. The tool holder was rotated to set angle α and tightened down to the compound.

e. From the position where the tool was tangent to the workpiece on a horizontal line, the tool was moved vertically a distance V and horizontally a distance H to simulate the angle β' as shown in Figure 8. Note that β is the true angle and β' is a projection of angle β on a plane perpendicular to the axis of the workpiece. (See Figure 5).

The preceding phase included additional testing to investigate other rotary disc edge geometries as shown in Figures 3 and 4. Other workpiece diameters were tested before developing and building the rotary cutter design and geometrical positioning. The data obtained from this phase were used as the basis for the following Flo-Turning investigation.

FLO-TURNING INVESTIGATION (Series SI, SII, A through M)

These series of tests were conducted to investigate the Flo-Turning process; they were conducted on two different engine lathes, and are described as follows:

1. American Pace Maker

   16 in. x 78 in.

   15 HP

2. Monarch

   13 in. x 54 in.

   20 HP

Special heads and fixtures were designed and built for the investigation.

Numerous HSS rotary discs were manufactured and heat treated. Also, 8 Carbide Disc Cutters were fabricated by the Adamas Carbide Corporation according to the project specifications.

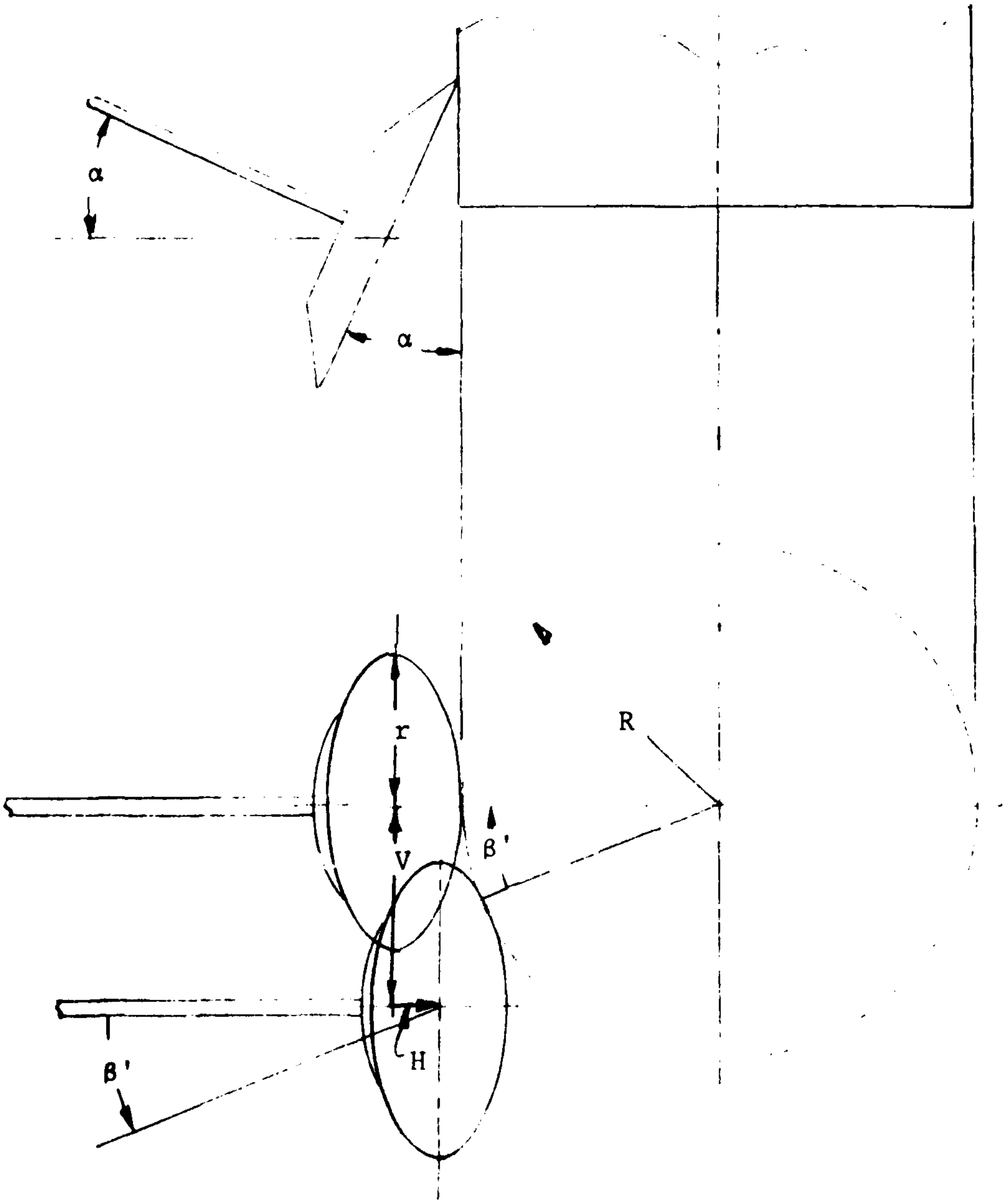


FIGURE 8. Cutting Tool Angles

Series SI

The first series (SI) of tests were conducted on the American Pacemaker engine lathe using a specially designed tool head with a 2" rotary disc.

The set-up for the Series SI tests consisted of a small conventional rotary cutter disc made of hardened high speed steel as shown in Figures 9 and 10. Two Timken tapered roller bearings were preloaded to reduce axial and radial backlash. The cutter was mounted at 45° with the axis of the workpiece and the edge of the rotary cutter entered the work material at the largest depth of cut (Figure 10). Such a position was dissimilar to previous researches on rotary discs. The positioning will cause an axial force which pulls the tool into the workpiece rather than pushing it away. However, with this cutting operation, the chip formation was similar to that of a single point tool turning operation except the chip cross section was dissimilar to the depth of cut/feed configuration.

The workpiece was a 5" bar stock of AISI 1045. The cutting conditions for the five tests which were run dry are shown in Table 1.

TABLE 1

CUTTING CONDITIONS FOR SERIES SI TESTS

Test No.	Speed SFPM	Feed IPR	Depth In.	Remarks
SI-1	140	.008	.020	See Figure 11
SI-2	140	.008	.040	
SI-3	140	.030	.040	
SI-4	600	.030	.040	
SI-5	600	.061	.040	

The cutter and the workpiece were not overheated even with the heavy conditions of test SI-5. Moreover, the chip cross sections do not conform to the d x f configuration. One dimension of the chip cross section (the one related to the feed value) was usually two or three times larger than the feed while the other dimension (related to depth of cut) was closer in value to the depth of cut. This observation indicates the difference between this metal removal (peeling) operations and a single point turning operation.

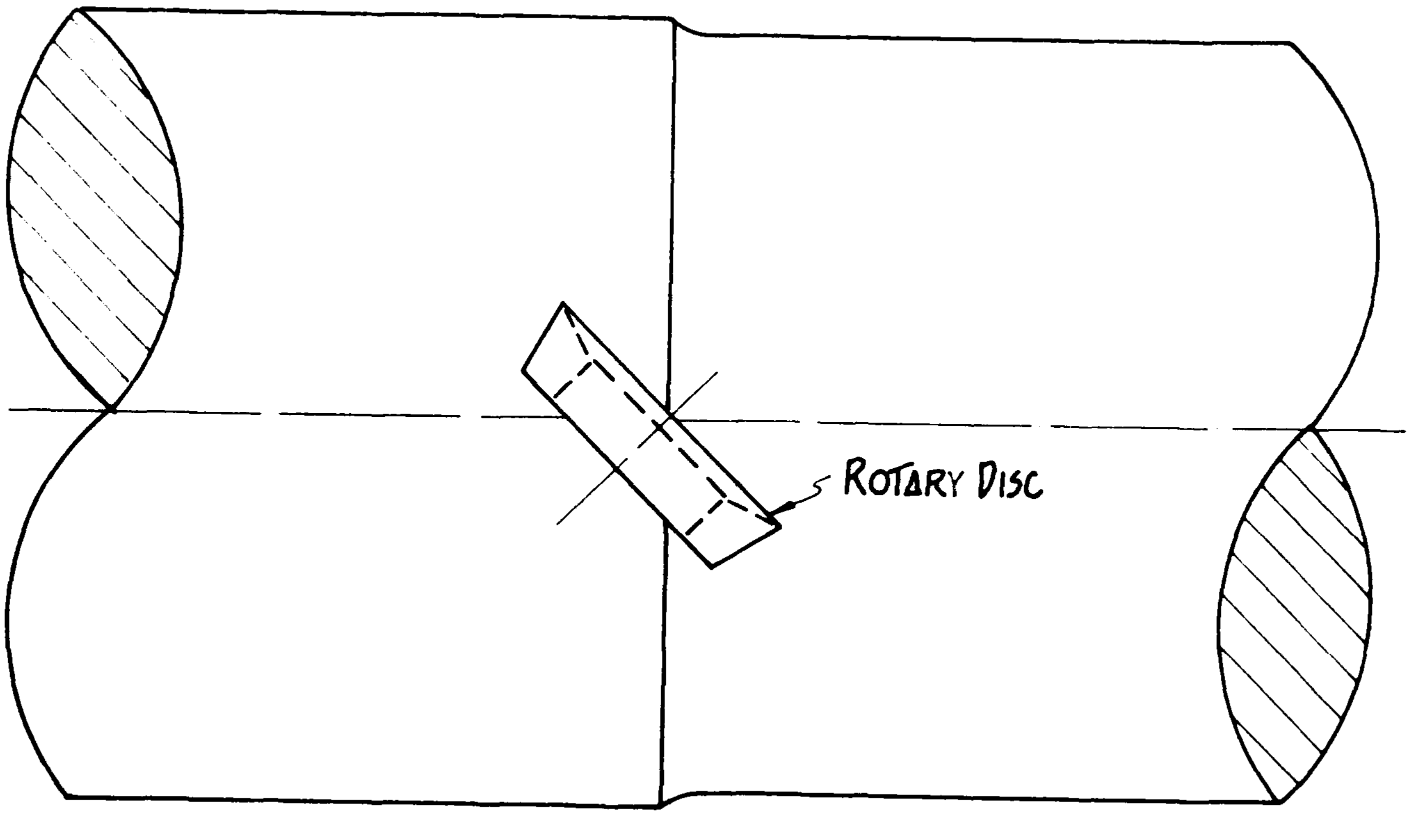


FIGURE 9. Positioning of Circular Disc Tool Relative to Workpiece (Test SI)

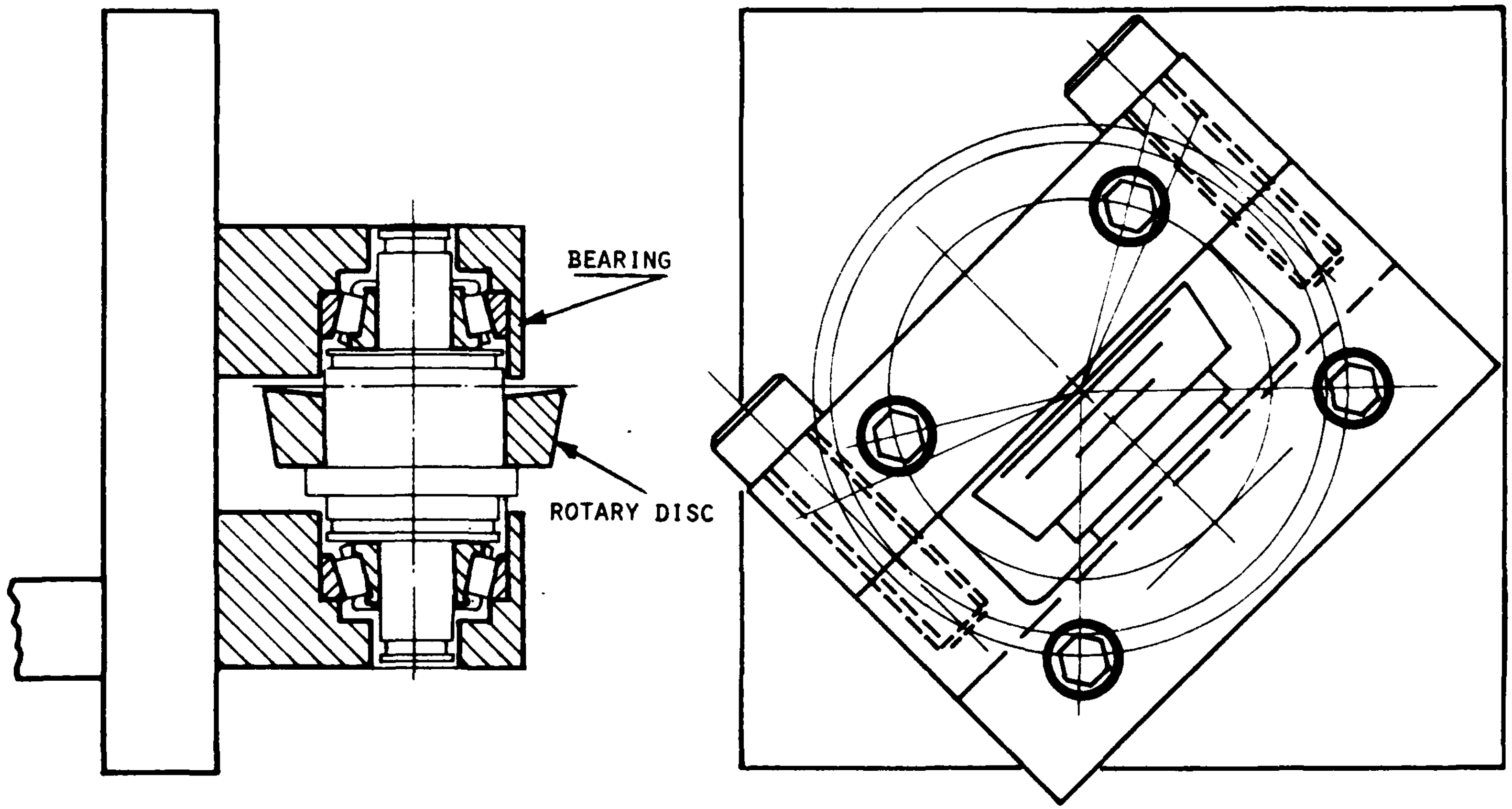
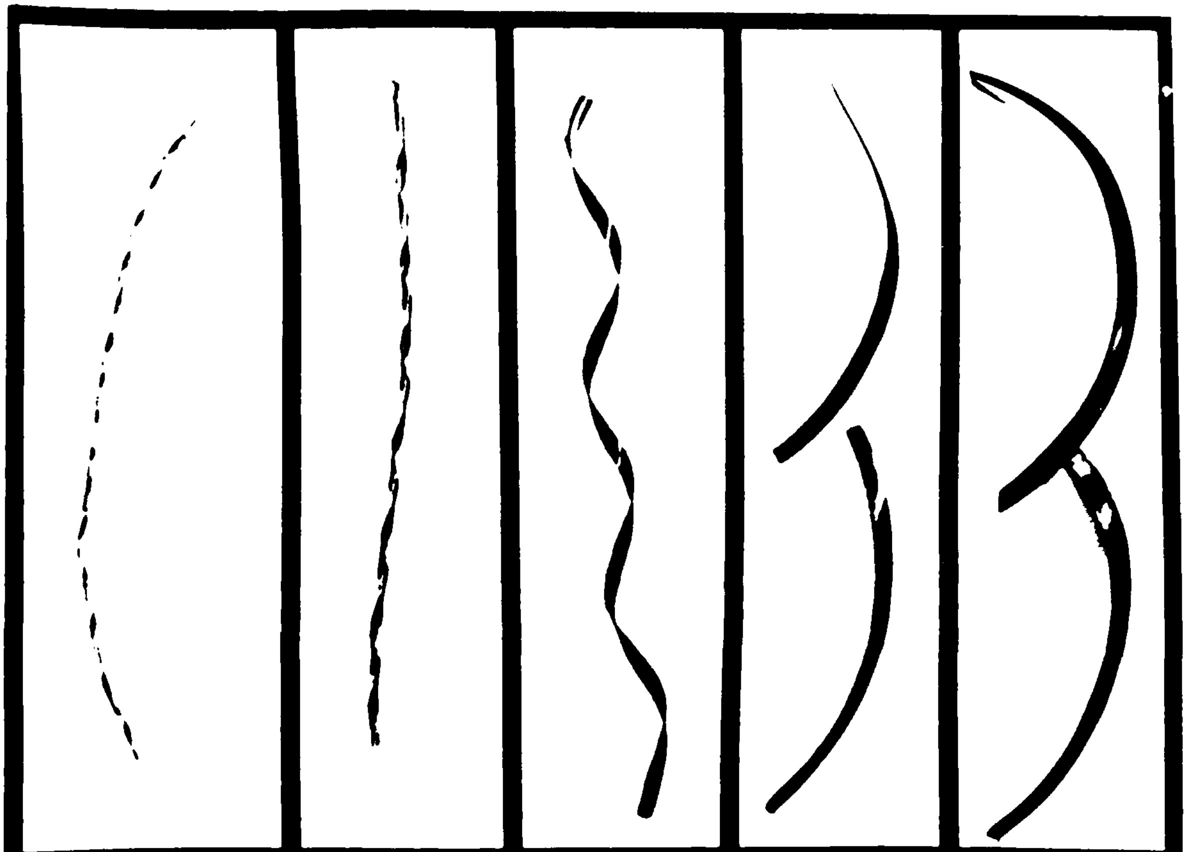


FIGURE 10. Circular Disc Tool Holder (Test SI)



Test #	SI,1	SI,2	SI,3	SI,4	SI,5
SFPM	140	140	140	600	600
Feed	.008	.008	.030	.030	.061
Depth	.020	.040	.040	.040	.040

FIGURE 11. Chip Formation for Tests SI, 1-5

Series SII

The second series (SII) of tests were conducted on the Monarch Engine Lathe provided by the project's sponsor. These series of tests used three different size rotary cutters of the same high speed steel.

The tool holder was designed to hold the self-rotating cutter at a four degree clearance angle with respect to the workpiece (See Figures 12 and 13) and to be adjustable along the axis of the cutter. An adjustment perpendicular to the axial direction was provided to accept various possible cutter diameters of 3 in. or less.

Later the three tool holders were attached to the bolster plate symmetrically about the workpiece as shown in Figure 13. The bolster plate is attached to the carriage. Figure 14 shows the cutter details.*

The following criteria was considered important in the design of the tool support system.

a. Rigidity of each tool holder support.

b. Symmetrical spacing of tools to balance the load on the workpiece.

c. Independent adjustment of each tool.

d. Ability of the system to hold the peeling tool as shown in Figures 12 & 13, and to hold milling cutters or grinding wheels for machining tests involving multi-cutting edge tools and grinding wheels.

Figures 15 through 18 illustrate the set-up of the flo-turning mechanism. Some of the key points to note on each of the pictures are:

Figure 15 illustrates three self-propelled cutter heads mounted on the bolster plate. Depth of cut adjustment is made on each head by turning the quill with a spanner wrench, one revolution (.050"). The slots on the cutter head base permits angularity adjustments for the circular cutters. Note the limitation of space between the lathe bed ways; this limited the size of the cutter heads that could be designed for the investigation.

Figure 16 illustrates a top view picture of the mechanism mounted on the saddle of the engine lathe.

Figure 17 shows the workpiece and cutter heads in position. The workpiece was prepared with a series of diametrical steps for the cutting experiments. The last turned surface near the head stock shows a typical surface cut.

* The cutter block head assembly is shown in detail in the Appendix.

Figure 18 illustrates the length of the workpiece. Due to vibrations, the workpiece had to be shortened. Vibration was identified in the tail-stock spindle and because of the age of the Monarch lathe, the spindle bearings were probably not in the best of condition.

In the aforementioned tests, the most severe cutting conditions were performed with minimal chatter. The tool holder system was redesigned to arrange three tools symmetrically about the workpiece as shown in Figure 13.

The three turning heads with the 3 in. high speed steel rotary discs were reworked and assembled.

After conducting test Series SI and SII, the balance of the flo-turning investigations were labelled alphabetically from A through M.

Table 3 summarizes the main features of tests A through Q. Tests N, O, P, and Q were conducted to investigate milling and grinding processes to be detailed later in the report.

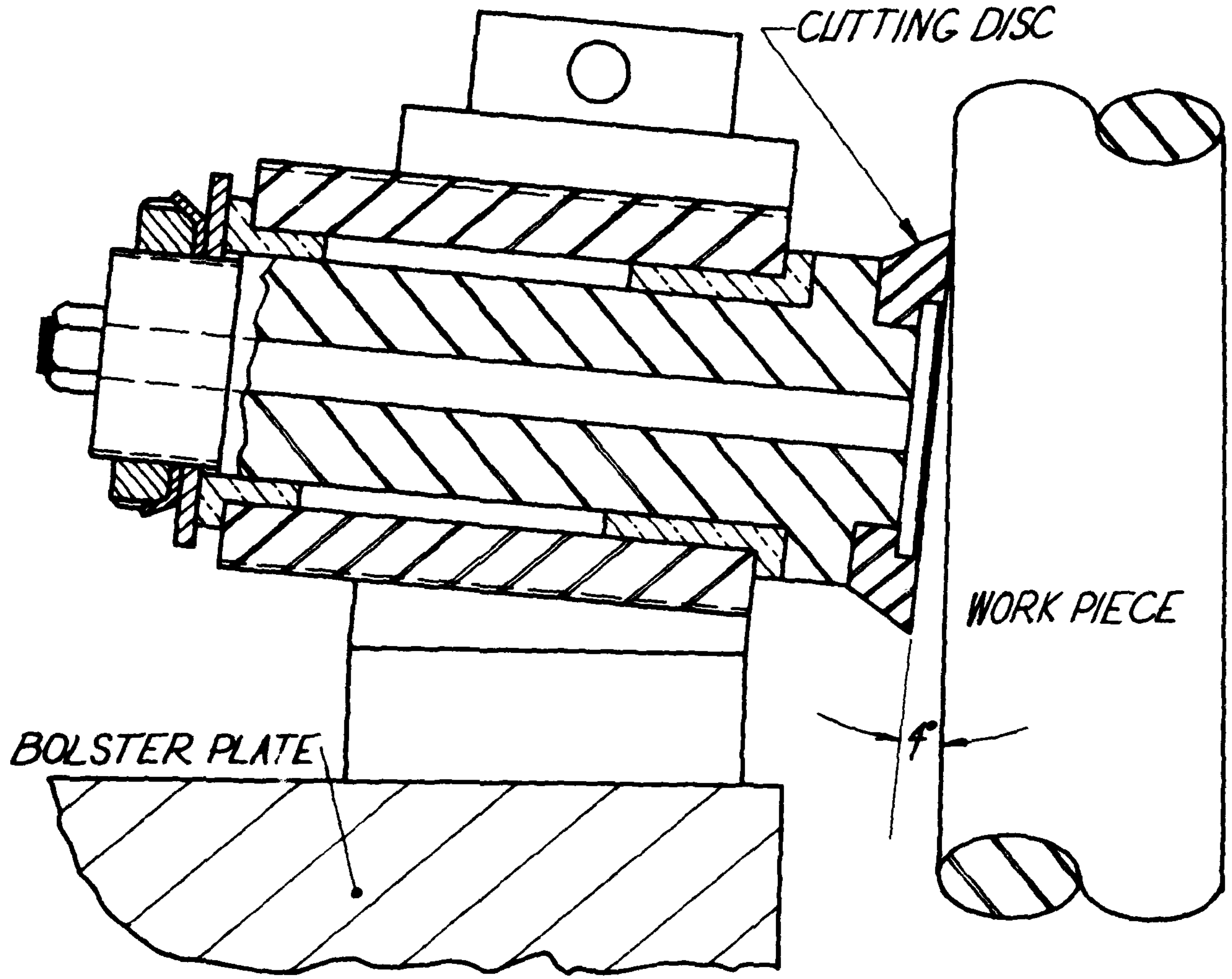


FIGURE 12. Top View-Section Turning Assembly

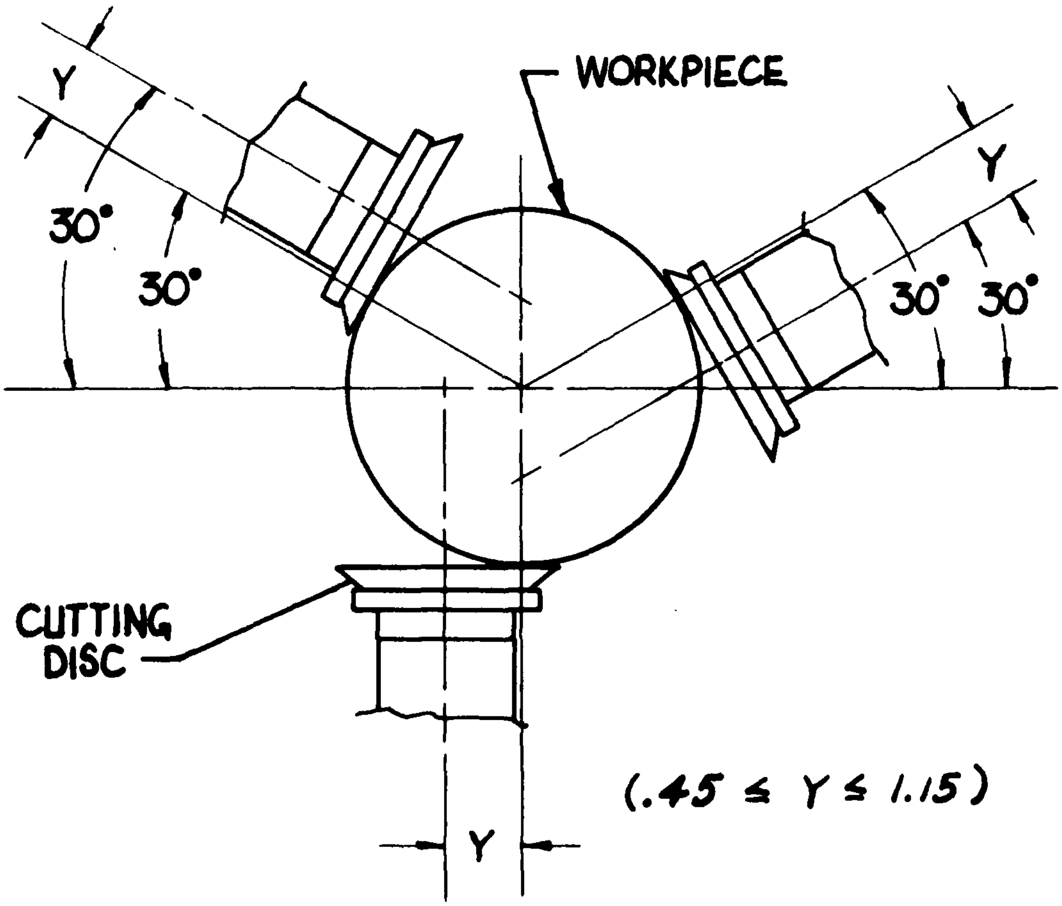


FIGURE 13. 3 Discs Position - Flo-Turning

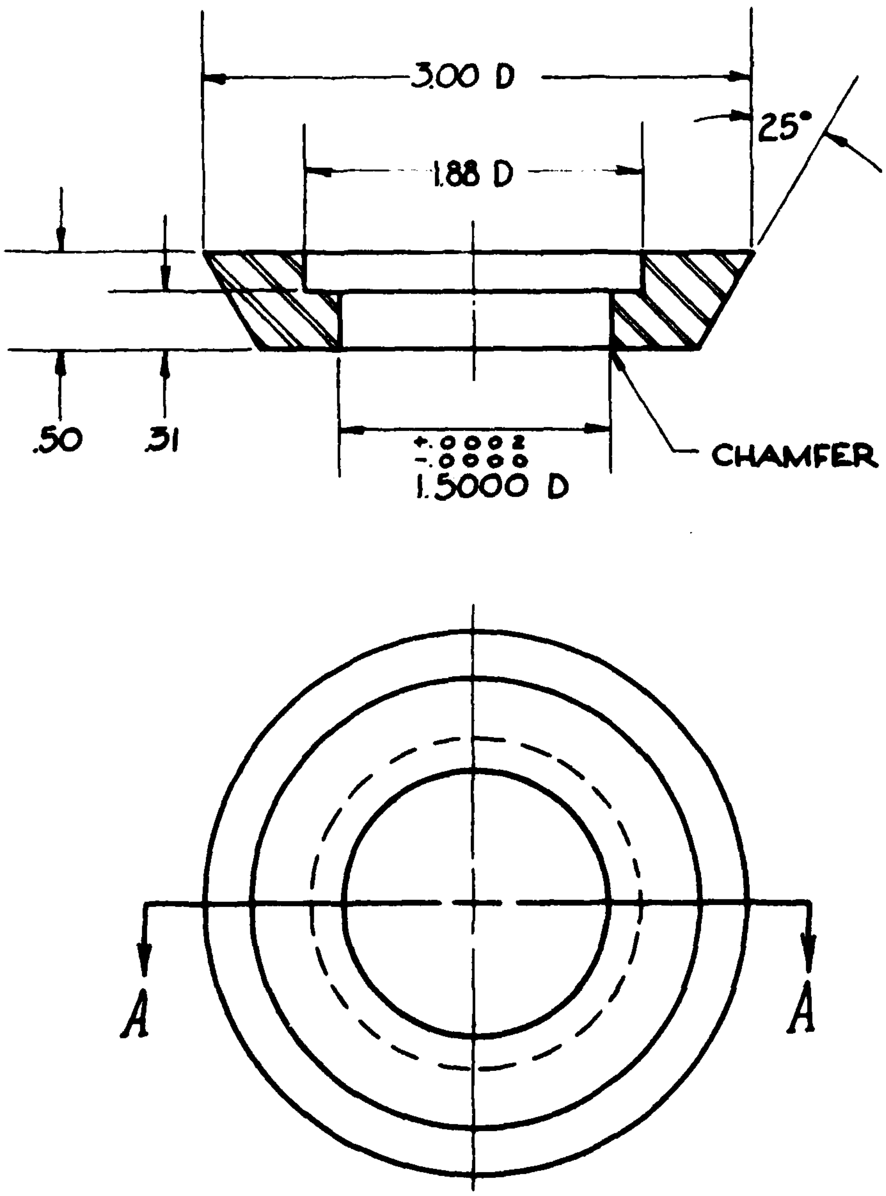


FIGURE 14. Circular Cutting Discs

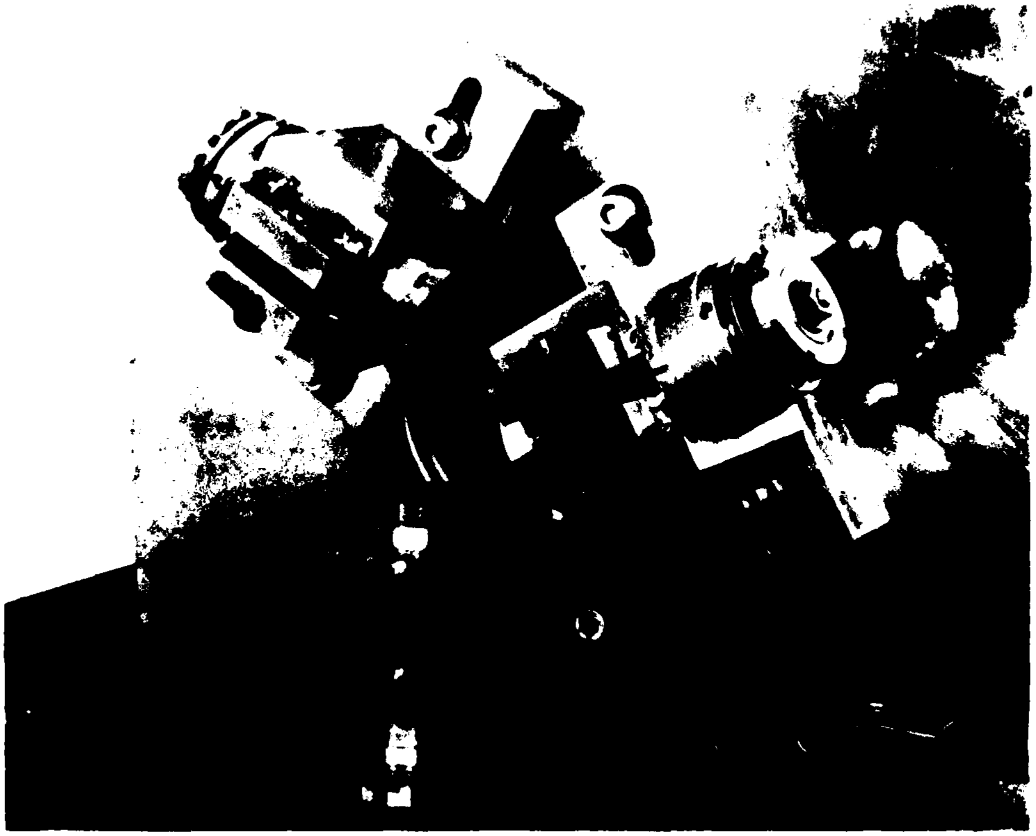


FIGURE 15. Self Propelled Cutter Heads

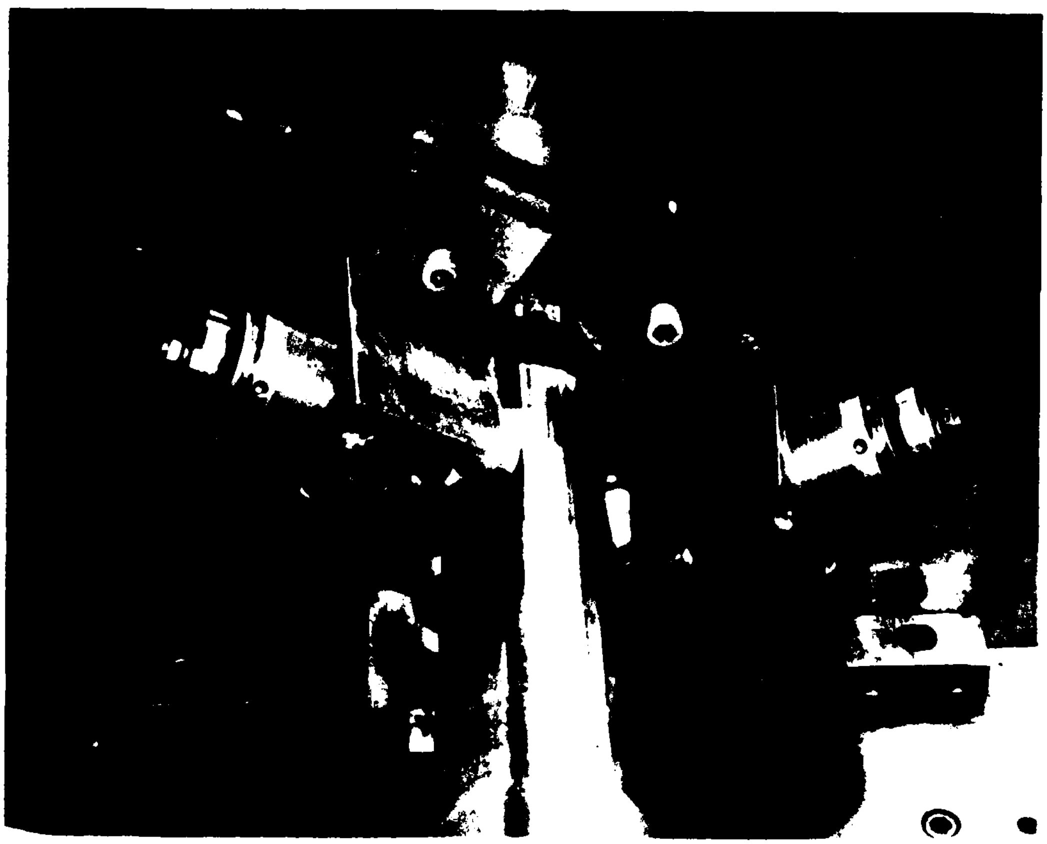


FIGURE 16. 3 Head Mechanism Setup

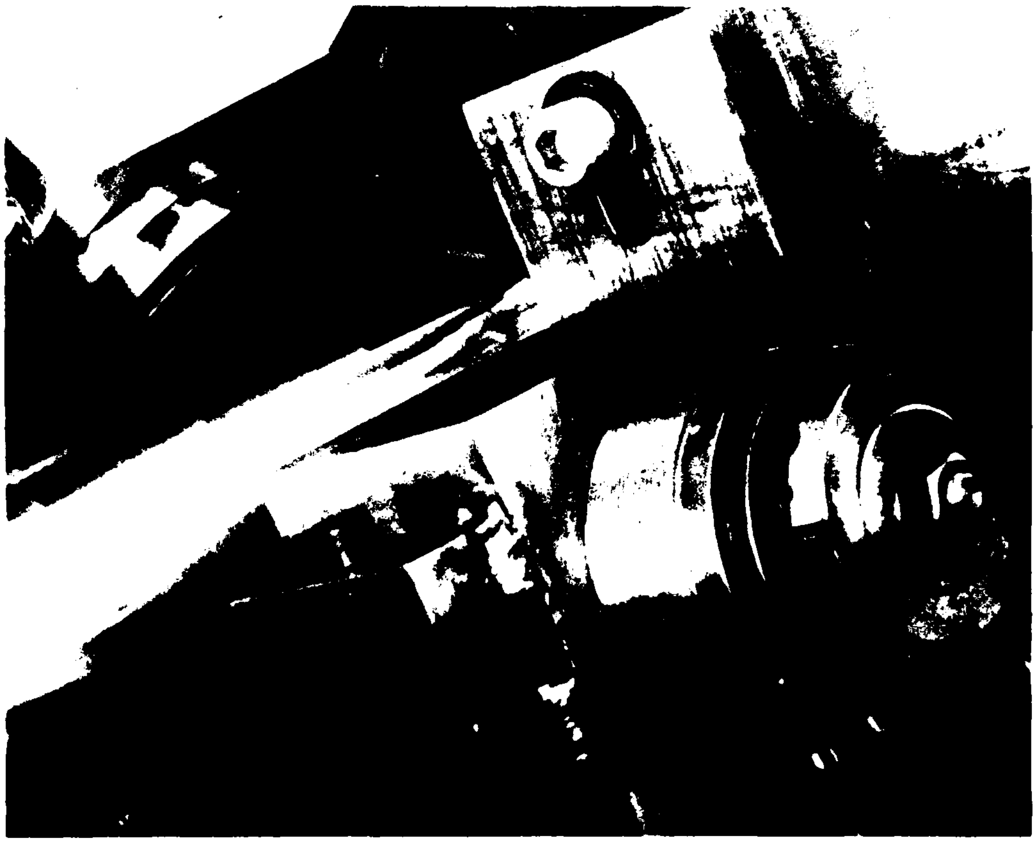


FIGURE 17. Workpiece and Cutter Heads in Cutting Position

FIGURE 18 Length of Workpiece in Turn Steps

All of these tests were run on AISI 4140 with or without coolant. A description of the 28 tests is presented in Table 2.

TABLE 2

CUTTING CONDITIONS FOR SII TESTS

TEST NO.	CUTTER DIAMETER in.	SPEED sfpm	FEED ipr	DEPTH in.	REMARKS
SII-1	3	100	.066	.050	
SII-2	3	100	.033	.050	
SII-3	3	100	.015	.050	head was loose, chatter
SII-4	3	200	.033	.050	head was loose, chatter
SII-5	3	315	.033	.050	
SII-6	3	500	.016	.050	
SII-7	3	500	.033	.050	
SII-8	3	1100	.016	.050	machine was overloaded
SII-9	3	500	.033	.050	3/4 load on machine
SII-10	3	250	.016	.050	light load, no coolant
SII-11	3	500	.016	.050	1/2 load, no coolant
SII-12	3	250	.033	.050	light load, no coolant
SII-13	3	500	.033	.050	7/8 load, no coolant
SII-14	3	1000	.016	.050	chattering, head loose
SII-15	1	30	.033	.050	cutter dulled, test stopped
SII-16	1	30	.033	.050	no coolant, rough SF
SII-17	1	100	.033	.050	with coolant, rough SF

TABLE 2 (cont.)

TEST NO.	CUTTER DIAMETER in.	SPEED sfpm	FEED ipr	DEPTH in.	REMARKS
SII-18	1	250	.033	.050	cutter broke
SII-19	2	30	.033	.050	no coolant
SII-20	2	100	.033	.050	with coolant
SII-21	2	200	.033	.033	with coolant
SII-22	2	250	.033	.050	with coolant
SII-23	2	30	.033	.050	head was shifted upward before test, better chips with coolant
SII-24	2	200	.033	.050	"
SII-25	2	30	.066	.050	"
SII-26	2	100	.066	.050	"
SII-27	2	250	.066	.050	cutter was pushed backwards
SII-28	2	250	.066	.060	cutter was pushed more

The chips removed from these 28 cutting tests were collected and are shown in Figures 19 through 25.

It was concluded, from these two series of tests and after examination of the chip formation and the surface finish of the workpieces, that the 3 diameter cutter, positioned as shown in Figure 12, performed better than the 2 in. and 1 in. diameter cutters.

TABLE 3

OUTLINE OF TEST METHODS AND VARIABLES

Test	Machine Tool	Description of main set-up of the test series and main objective	# of test runs
A	Monarch	one HSS turning disc (disc position Y = .95")	18
B	Monarch	one HSS turning disc (disc position Y = .75") investigate several cutting conditions	25
C	Monarch	one HSS disc (investigate optimal cutter position with a set of cutting conditions)	11
D	Monarch	one HSS disc (same as series C) investigate cutter position with a different set of cutting conditions	9
E	Monarch	one HSS disc (with the optional cutter position obtained from Series C,D) Keep the MRR constant at 3 in^3/min. and investigate the best combinations of speed, feeds, and depths of cut for the best finish and the least power consumed (E11 and E13 gave the best result)	15
F	Monarch	2 HSS turning (free wheeling) disc cutting simultaneously (one in the front and one in the rear) and investigate different cutting conditions	11
G	Monarch	2 HSS turning discs - staggered (a leader and a follower) with axial difference of .042"	4
H	Monarch	Single point carbide tool inserts in holder fixed to the Bolster plate - to compare their UHP and S: with the rotary disc.	5
I	Monarch	A carbide rotary disc--to compare its performance with a HSS disc	5
J	Monarch	Investigate vibration (displacement of several parts on the set-up)	2

TABLE 3 (Cont.)

Test	Machine Tool	Description of main set-up of the test series and main objective	# of test runs
K	Monarch	Single Carbide disc investigate optimal positioning of the disc	4
L	Monarch	Without pre-set test conditions, investigate cluster of 3 HSS cutters working individually as well as double and triple	14
M	Monarch	Without pre-set test conditions--to further investigate the cluster of 3 HSS discs evaluating the limitation of the set-up as well as the engine lathe carriage design in accommodating for non-conventional force systems	6
N	Monarch	A single triangular HSS milling cutter fixed in a special head driven by a hydraulic motor fixed on the bolster plate and driven by a 10 HP hydraulic pump	19
O	Monarch	A Brown & Sharpe Carbide Milling Cutter replaced a HSS cutter in the same set-up described in Series N	4
P	American Pace Maker	Another B. & S. Carbide Milling cutter was fixed on a special spindle driven by a 5 HP electric motor and fixed on the carriage of the Pace Maker Lathe (with relatively higher speeds)	5
Q	American Pace Maker	EXPERIMENTAL RESEARCH ON GRINDING A special grinding wheel was fixed in a special spindle driven by a 5 HP electric motor and set on the carriage of the Pace Maker	5

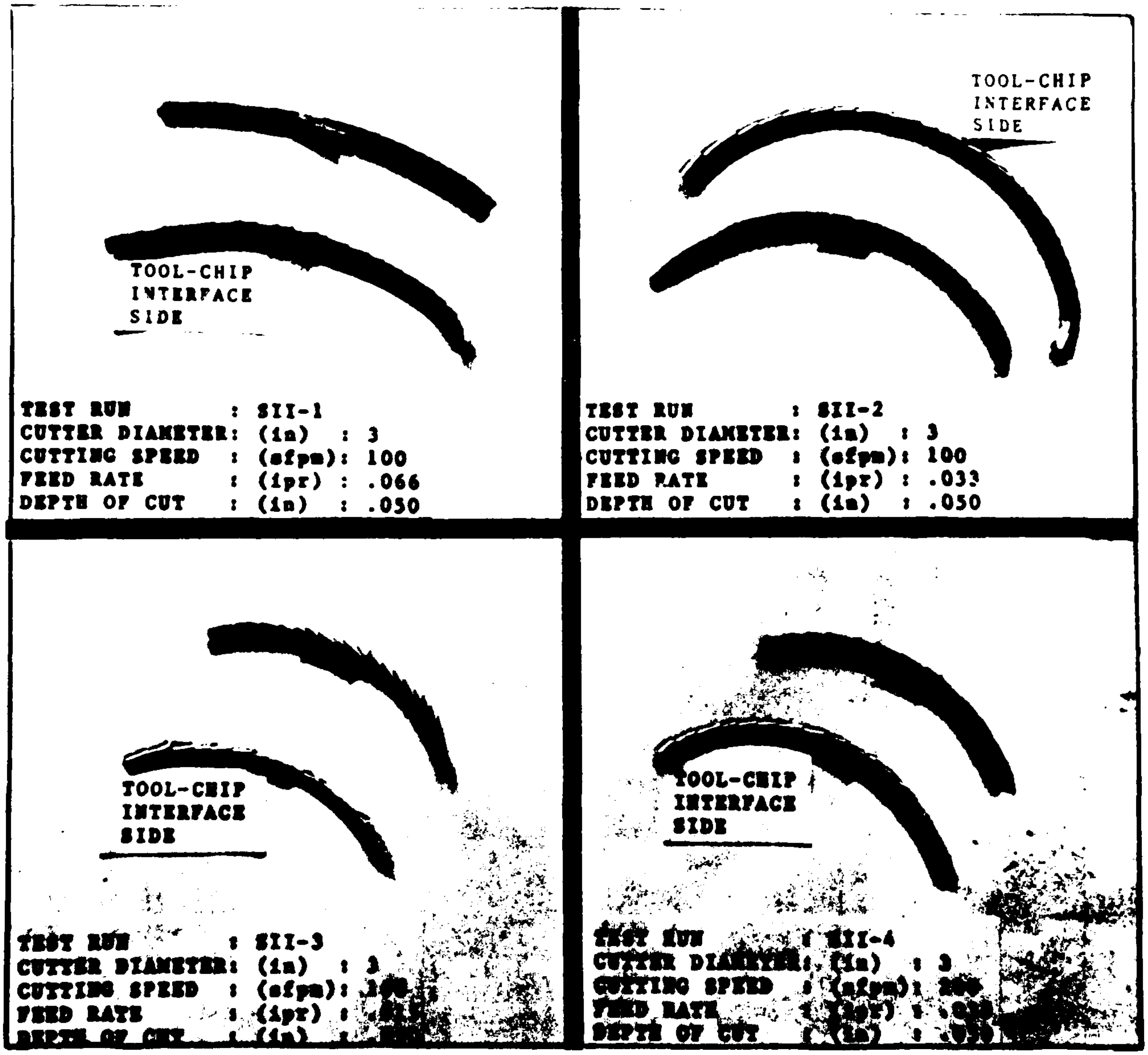


FIGURE 19. Chip Formation for Tests SII, 1-4

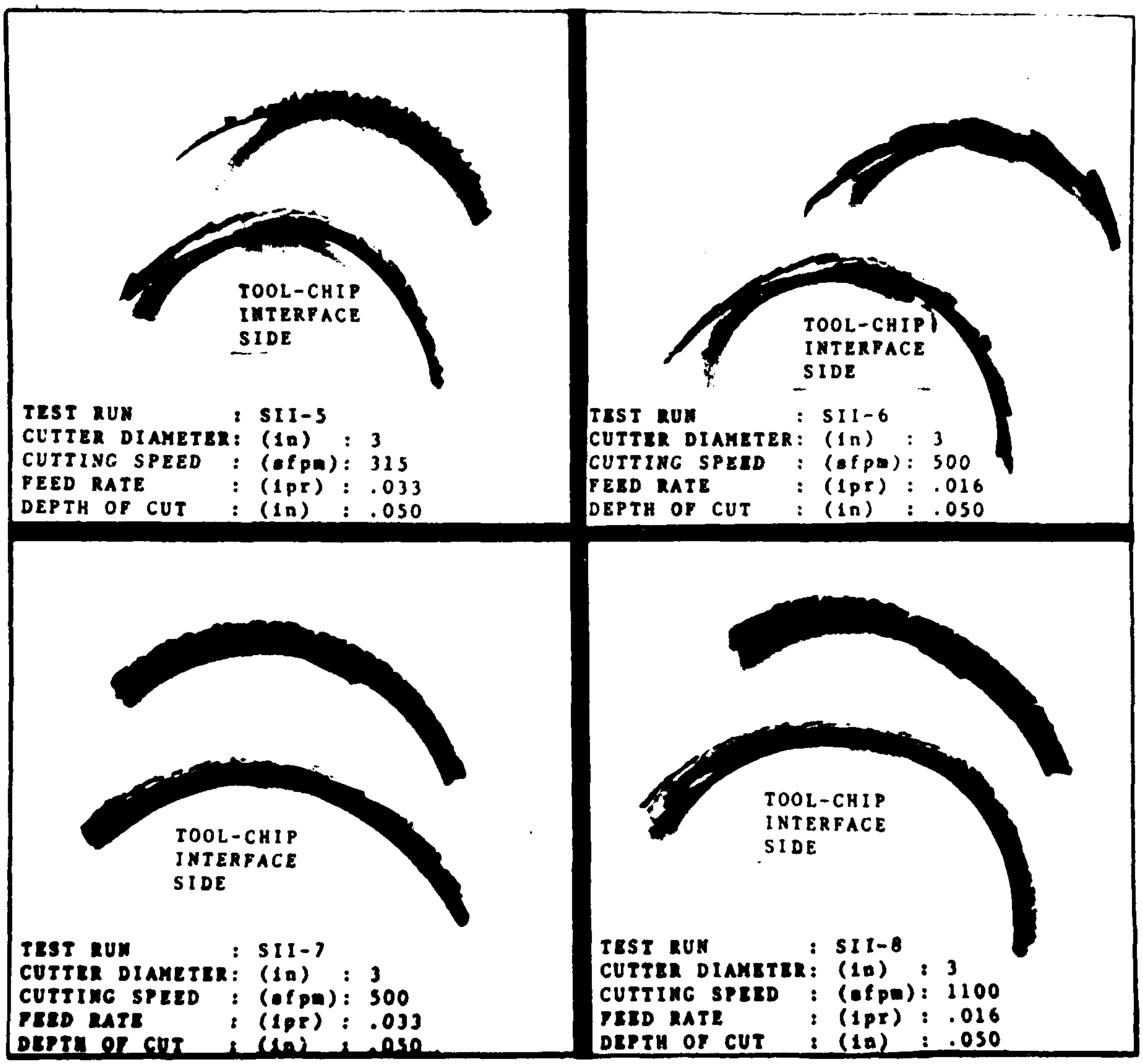


FIGURE 20 Chip Formation for Tests SII, 5-8

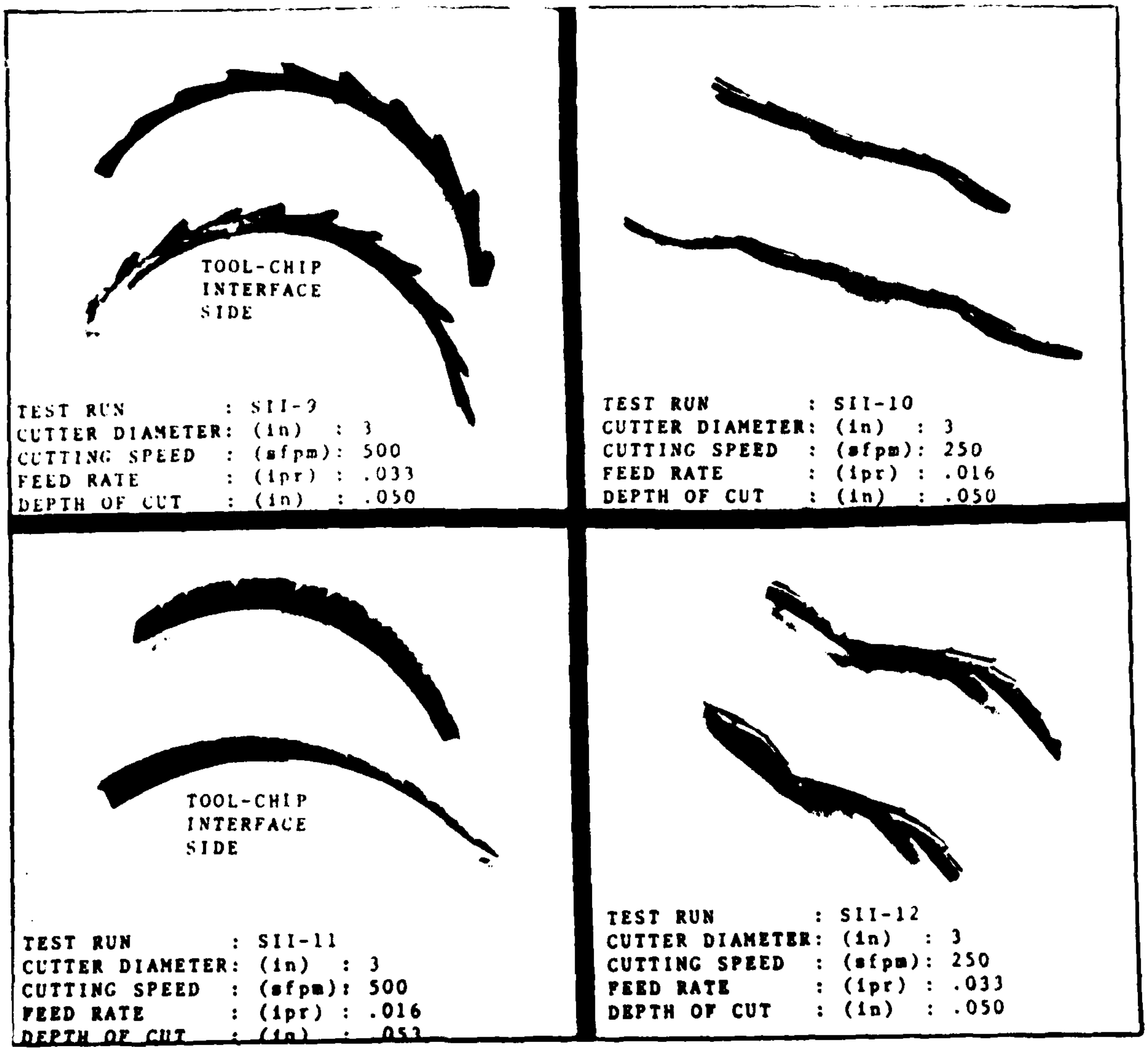


FIGURE 21. Chip Formation for Tests SII, 9-12

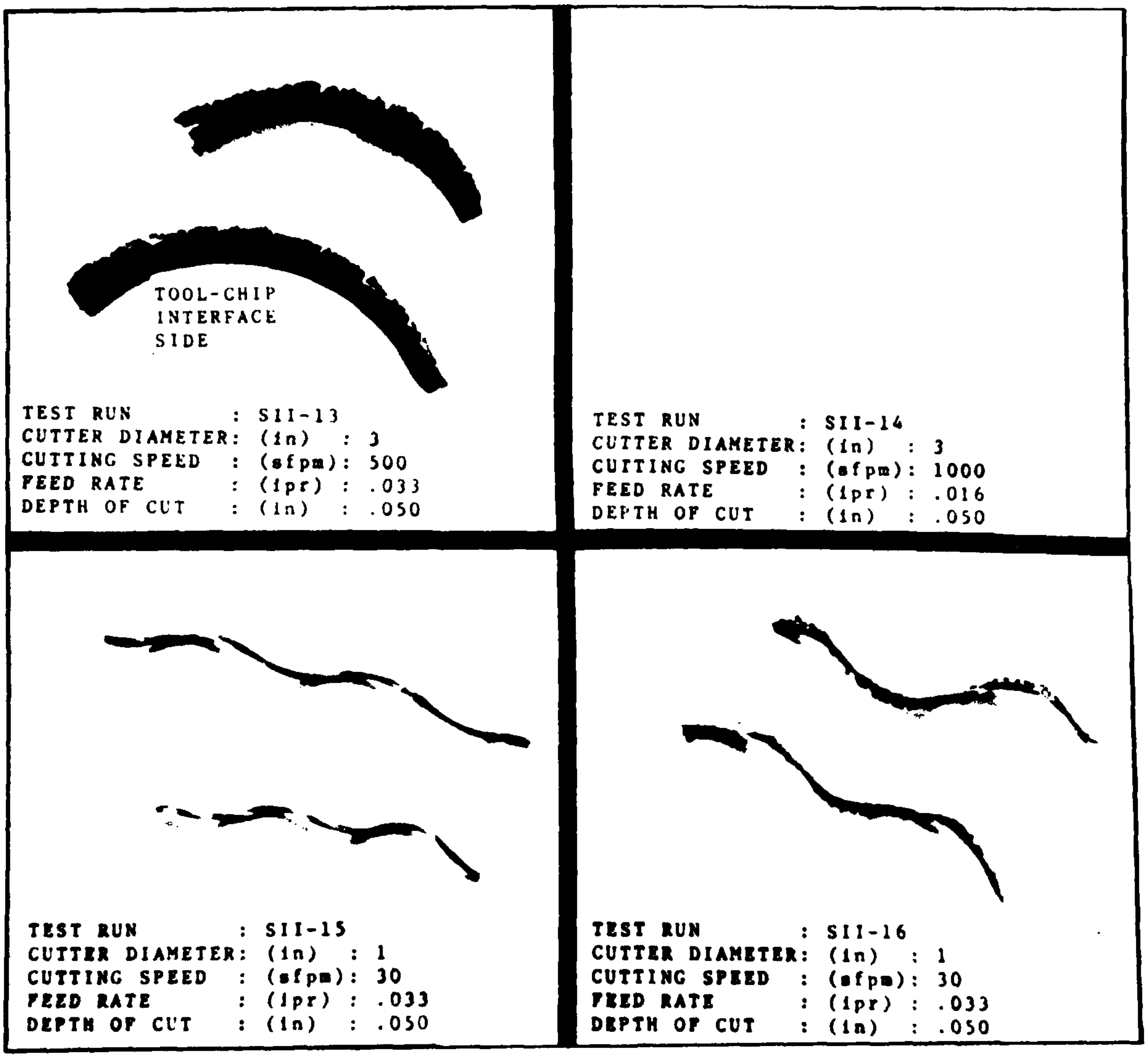


FIGURE 22 Chip Formation for Tests SII, 13-16

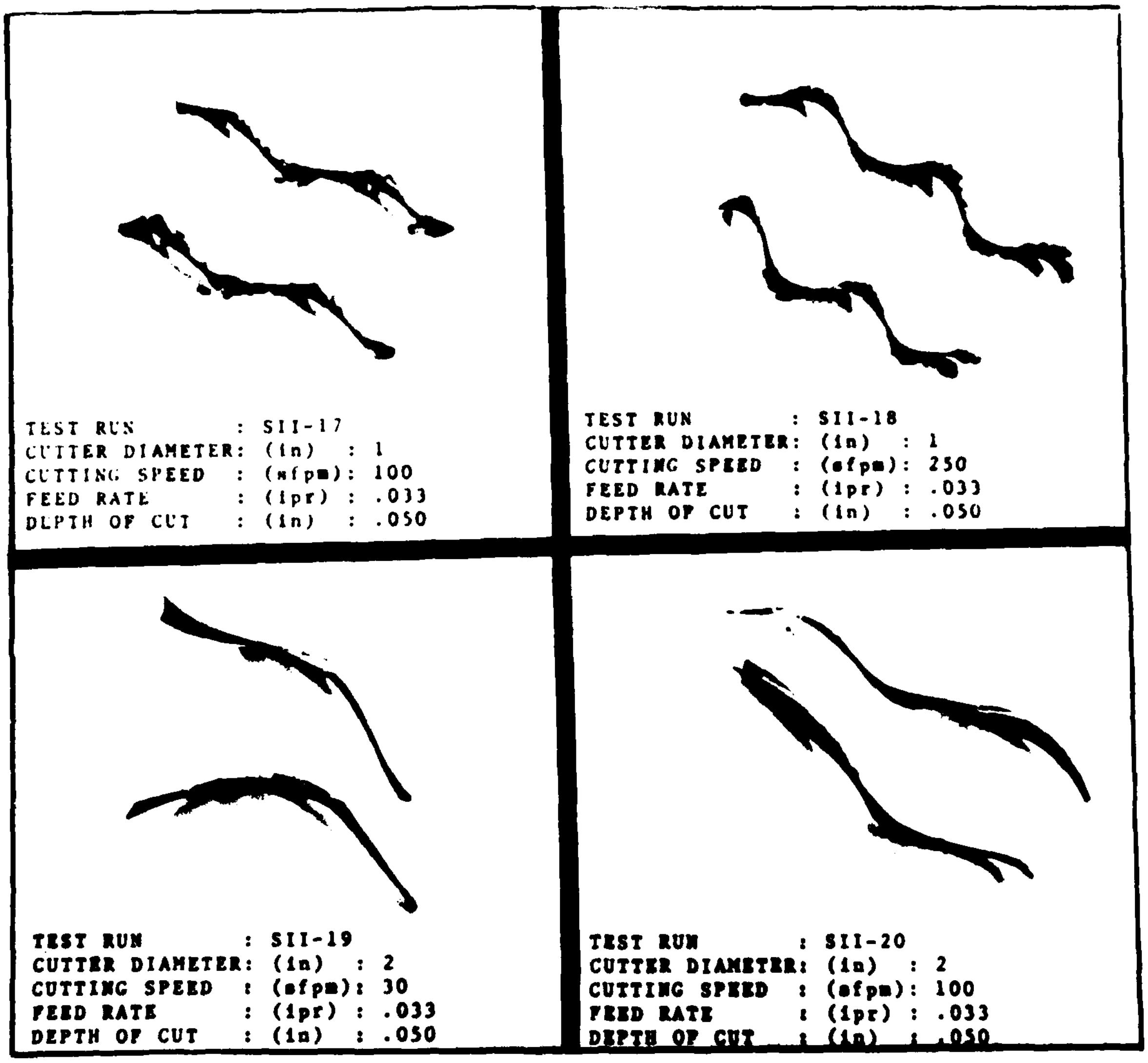


FIGURE 23. Chip Formation for Tests SII, 17-20

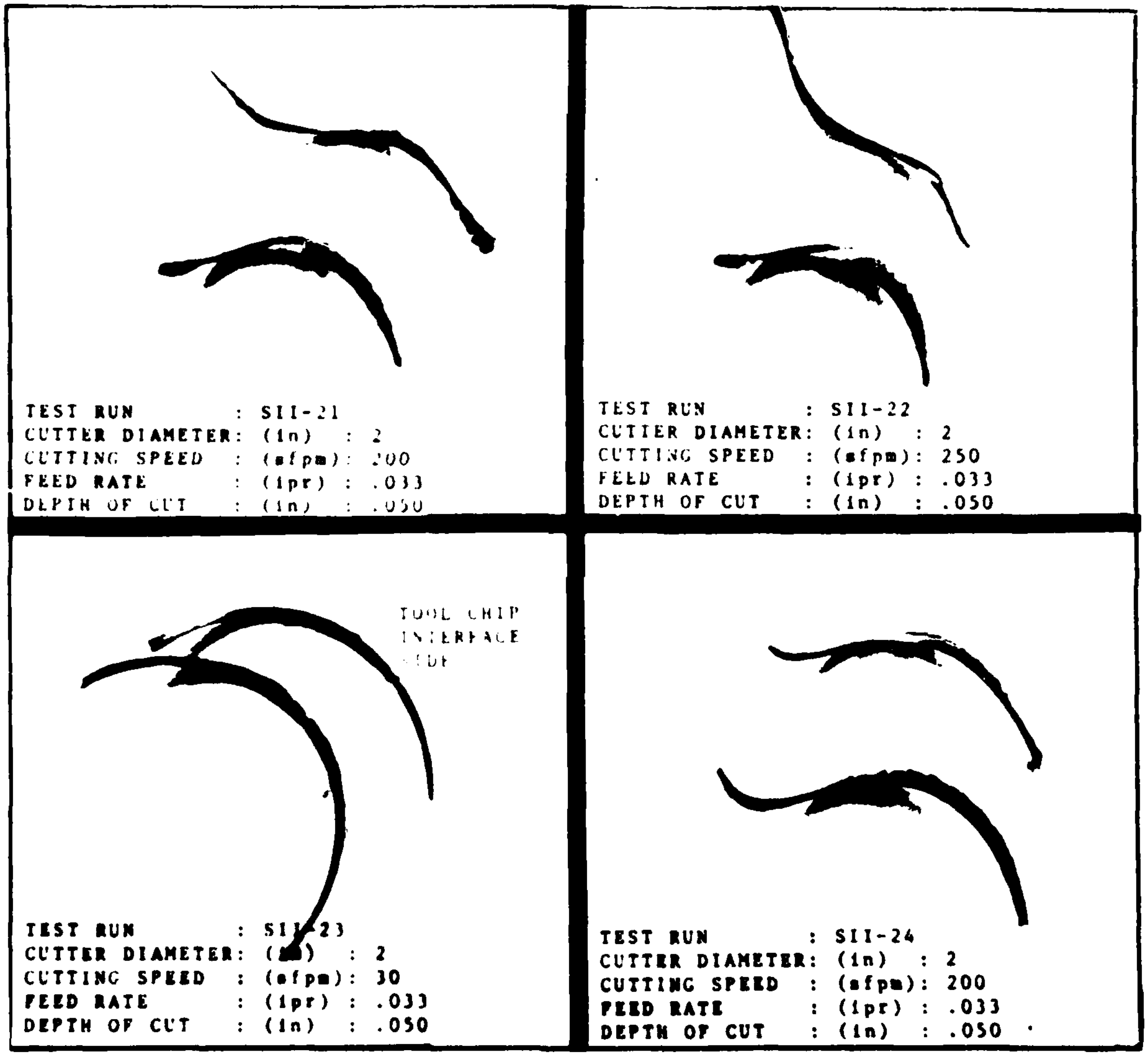


FIGURE 24. Chip Formation for Tests SII, 21-24

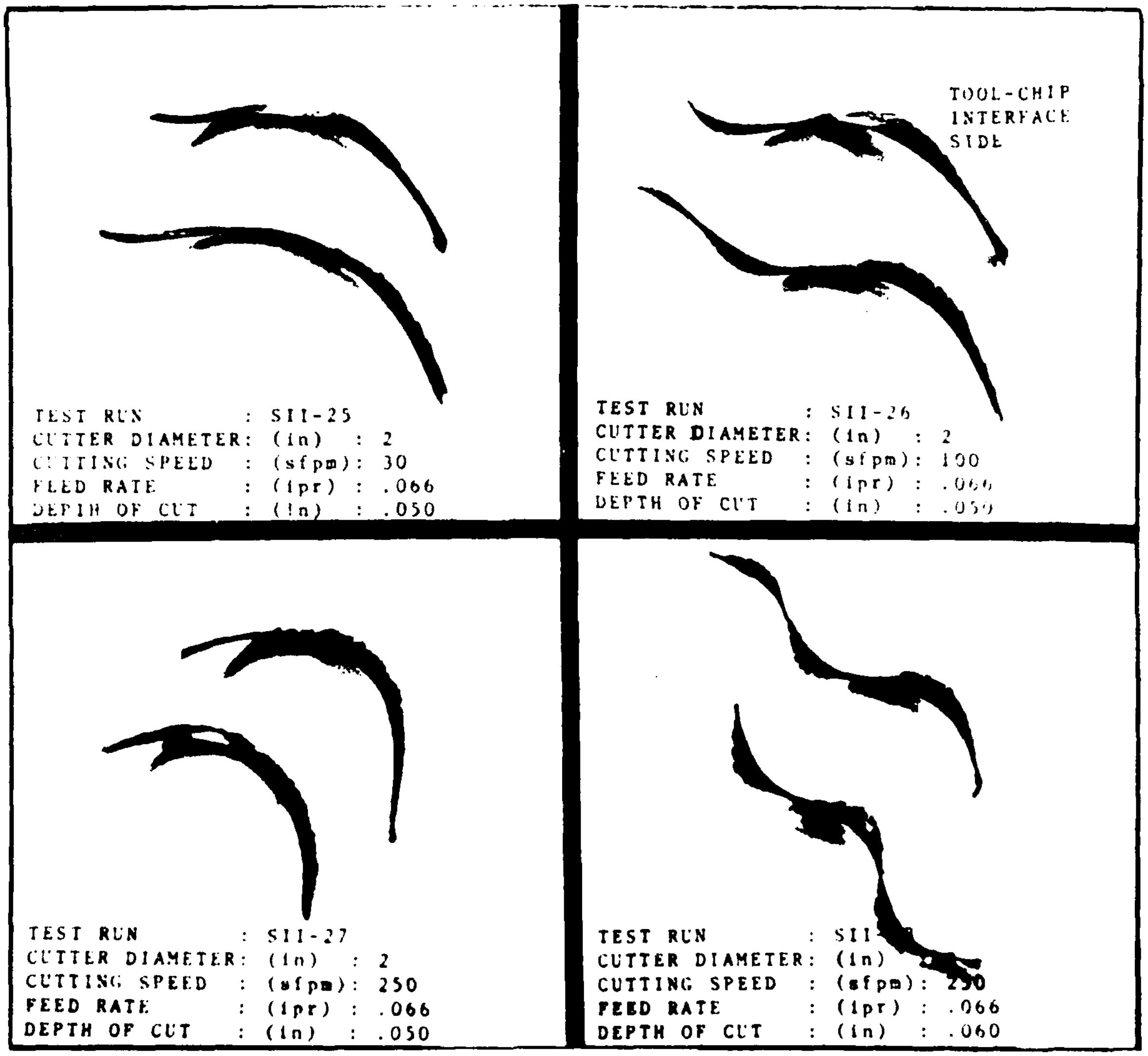


FIGURE 25. Chip Formation for Tests SII, 25-28

Series A through M

Each of the series of tests A through M is detailed to include the following information:

a. cutting conditions (independent variables)

b. the following dependent variables were chosen:

1. Unit or specific HP in $HP/in^3/min$.

2. Surface finish (RMS).

3. Additional visual observation.

Series A

These tests incorporated one head with a rotary HSS Disc cutter. Twelve treatment combinations were run with speeds ranging from 100 to 500 SFPM; feed of .016 and .033 ipr and depths of cut of .020, .030, and .050 inches. All the tests were considered successful with relatively fair surface finish of 100 to 250 microinches. The power consumed was measured in all the 12 runs. The specific HP (amount of HP needed to remove one cubic inch every minute from the workpiece) ranged from .7 to 1.2 HP.

Constant parameters:

a. Work Material: AISI 1045 Rockwell C 15

b. Cutter Position: Y=.95 in. (Refer to Figure 13)

c. Cutter: 3 in. HSS

Independent Variables:

a. Speed: 100- 300- 500 SFPM

b. Feed: .0166- .033 ipr

c. Depth: .020- .035 -.050 in. (12 original test runs)

Test numbers for various combinations of speeds, feeds and depths are given in Table 4.

TABLE 4

STATISTICAL DESIGN FORMAT FOR SERIES A

Feed	.016	.016	.033	.033
Depth / Speed	.050	.020	.035	.050
100	1	4	7	10
300	2	5	8	11
500	3	6	9	12

Results of Series A tests are given in Table 5.

TABLE 5

SERIES A TEST RESULTS

TEST NUMBER	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
A-1	.0166	.0505	100	1.007	4.428	1.07	1.06	100-110	.95
A-2	.0166	.0505	300	3.02	4.327	4.16	1.37	160	"
A-3	.0166	.0495	500	4.95	4.226	5.63	1.14	300	"
A-4	.033	.021	100	.83	4.127	.81	.97	200	"
A-5	.033	.019	300	2.02	4.085	2.14	1.06	200	"
A-6	.033	.00[illegible]	500	1.39	4.047	1.34	.96	200	"
A-6 repeat	.033	.0215	500	4.27	4.033	3.62	.85	250-300	"
A-7	.033	.034	100	1.34	3.990	1.07	.80	200	"
A-8	.033	.0355	300	4.22	3.922	4.42	1.04	200	"
A-9	.033	.0365	500	7.23	3.851	6.57	.91	200	"
A-10	.033	.0505	100	2.00	3.578	1.48	.74	150-200	"

TABLE 5 (Cont.)

TEST NUMBER	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
A-11	.033	.049	300	5.83	3.676	5.50	.94	300	.95
A-12	.033	.051	500	10.[illegible]	3.778	7.50	.74	400	.95

Series B

Constant Parameters:

a. One HSS rotary disc cutter

b. Work material: AISI 4140 Rockwell C 30

c. Cutter position: Y = .75 in.

Independent Variables:

a. Speed: 100 - 300 - 500 SFPM

b. Feed: .010 - .016 - .024 ipr

c. Depth: .020 - .035 - .050 in.

Test numbers for various combinations of speeds, feeds and depths are given in Table 6.

TABLE 6

STATISTICAL DESIGN FORMAT FOR SERIES B

Speed	100			300			500		
Feed \ Depth	.020	.035	.050	.020	.035	.050	.020	.035	.050
.0102	1	2	3	10	11	12	19	20	21
.0166	4	5	6	13	14	15	22	23	24
.0242	7	8	9	16	17	18	25	26	27

Results of Series B tests are given in Table 7.

TABLE 7

SERIES B TEST RESULTS

TEST NUMBER	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
B-1	.0102	.023	100	.281	4.903	.27	.961	60	.75
B-2	.0102	.036	100	.441	4.857	.47	1.065	80	"
B-3	.0102	.0505	100	.618	4.785	.94	1.52	200	"
B-3 repeat	.0102	.049	100	.599	4.684	.536	.896	150	"
B-4	.0166	.0195	100	.389	4.586	.268	.688	150	"
B-5	.0166	.041	100	.817	4.547	.536	.656	130	"
B-6	.0166	.0515	100	1.026	4.903	1.21	1.18	100-150	"
B-7	.0242	.0145	100	.442	4.808	.268	.636	125	"
B-8	.0242	.033	100	.958	4.771	1.34	1.4	200	"
B-9	.0242	.0505	100	1.48	4.704	$\frac{2.01}{1.61}$	$\frac{1.36}{1.1}$	150	"
B-10	.0102	.018	300	.662	4.605	.537	.81	100	"

TABLE 7 (Cont.)

TEST NUMBER	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
B-11	.0102	.0345	300	1.27	4.569	1.208	.95	90-100	.75
B-12	.0102	.056	300	2.06	4.905	3.35	1.62	100	"
B-13	.0166	.0185	300	1.105	4.793	.67	.606	100	"
B-14	.0166	.036	300	2.15	4.756	1.74	.808	90	"
B-15	.0166	.0395	300	2.36	4.684	3.48	1.48	200	"
B-15 repeat	.0166	.061	300	3.65	4.605	2.68	.734	200	"
B-16	.0242	.0215	300	1.88	4.904	1.61	.858	110	"
B-17	.0242	.0355	300	3.09	4.861	$\frac{3.4}{4.0}$	$\frac{1.08}{1.3}$	110	"
B-18	.0242	.0505	300	4.41	4.790	6.7	1.52	bad finish	"
B-19	.0102	.022	500	1.35	4.397	1.07	.793	80	"
B-20	.0102	.0365	500	2.24	4.353	2.41	1.08	70	"

TABLE 7 (Cont.)

TEST NUMBER	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
B-21	.0102	.0505	500	3.09	4.280	$\frac{5.22}{7.25}$	$\frac{1.69}{2.34}$	cutter failed	.75
B-22	.0166	.018	500	3.53	4.244	1.74	.97	150	"
B-23	.0166	.0355	500	3.53	4.244	3.49	.99	100-120	"
B-24	no test								
B-25	.0242	.020	500	3.05	4.173	2.71	.89	110	.75

Series C

Objective: Investigate the variable positions of the cutter with respect to the workpiece.

Constant Parameters:

a. Workpiece: AISI 4140 Rockwell C 30

b. One HSS rotary cutter

c. Speed: 300 SFPM

d. Feed: .0166 ipr

e. Depth: .020 in.

f. No coolant

Independent Variables:

a. Cutter position: Y = .45 - .55 - .65 - .75 - .85 - .95 - 1.05 - 1.15 in.

Results of Series C tests are given in Table 8.

TABLE 8

SERIES C TEST RESULTS

TEST	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORKPIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
C-1	0166	.0195	300	1.165	4.395	.938	.805	100	.85
C-2	"	.023	300	1.374	4.356	1.07	.78	100	.95
C-3	"	.0175	300	1.045	4.310	.85	.81	120	1.05
C-4	"	.023	300	1.38	4.275	1.2	.87	150	1.15
C-5	"	.0245	300	1.41	4.229	1.07	.73	100	.85
C-1 repeat									
C-6	"	.020	300	1.20	4.179	1.07	.89	140	.75
C-7	"	.026	300	1.56	4.139	1.07	.69	140	.75
C-6 repeat									
C-8	"	.0195	300	1.17	4.087	1.21	1.04	90	.65
C-9	"	.019	300	1.14	4.395	1.34	1.17	70	.65
C-8 repeat									
C-10	"	.021	300	1.26	4.357	1.34	1.06	90	.55
C-11	"	.0345	300	2.10	4.315	2.4	1.15	---	.45

Series D

Objective: Same as in Series C, except for a different set of conditions.

Constant Parameters:

a. Workpiece: AISI 4140 Rockwell C 30

b. One HSS rotary cutter

c. Speed: 300 SFPM

d. Feed: .0102 ipr

e. Depth: .035 in.

f. No coolant

Independent Variables:

a. Cutter Position: .55 - .65 - .75 - .85 - .95 - 1.05 in.

Results of Series D tests are given in Table 9.

TABLE 9

SERIES D TEST RESULTS

TEST NUMBER	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
D-1	.0102	.0375	300	1.38	4.227	2.14	1.55	90	.65
D-2	"	.031	300	1.14	4.152	1.34	1.17	80	.75
D-3	"	.036	300	1.325	4.090	1.61	1.21	70	.85
D-4 D-3 repeat	"	.0345	300	1.27	4.395	1.34	1.05	70	.85
D-5	"	.035	300	1.29	4.326	2.01	1.55	110	.95
D-6	"	.035	300	1.29	4.256	2.01	1.55	110	1.05
D-7	"	.0375	300	1.38	4.186	1.74	1.26	110	.55
D-8 D-1 repeat	"	.0375	300	1.38	4.111	1.74	1.26	120	.65
D-9	"	.0385	300	1.42	4.394	2.01	1.42	120	.90

Series E

Objective: To find the best "ball park" to cut 3 $in.^3$/min./cutter.

Constant Parameters:

a. Workpiece AISI 4140 Rockwell C 30

b. One HSS rotary cutter

c. Metal removal rate = 3 $in.^3$/min. (approximately)

d. No coolant (except for E-11, E-12, and E-13)

e. Y = .85 in.

Independent Variables:

a. Feed: .066 - .0355 - .0242 - .0166 - .0102

b. Depth: .065 - .060 - .050 - .040 - .035 - .030 - .025 - .020 - .015 in.

c. Speed: 95 to 1000 SFPM as required to achieve desired metal removal rate

Note: Tests E-14 and E-15 were run with a special cutter with a chip breaking circumferential groove. However, the groove failed to break or help in breaking the chips.

Results of Series E tests are given in Table 10.

TABLE 10

SERIES E TEST RESULTS

TEST NUMBER	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
E-1	.066	.0215	190	3.24	4.875	2.81	.868	180	.85
E-2	.066	.0305	125	3.05	4.832	3.49	1.14	140	.85
E-3	.066	.0375	95	2.81	4.771	3.49	1.24	110	.85
E-4	.0355	.0605	116	3.02	4.696	3.89	1.29	170	.85
E-5	.0242	.0595	173	3.0	4.575	3.62	1.206	130	.85
E-6	.0166	.0595	251	2.98	4.456	3.89	1.305	100	.85
E-6 repeat	.0166	.065	251	3.25	4.337	4.82	1.48	120	.85
E-7	.0102	.058	409	2.9	4.207	4.69	1.62	50	.85
E-7 repeat	.0102	.060	409	3.02	4.874	4.56	1.51	60	.85
E-8	.0102	.024	1000	3.0	4.752	5.22	1.74	40-50	.85
E-9	.0166	.013	1000	2.6	4.704	4.15	1.6	40-50	.85

TABLE 10 (Cont.)

TEST NUMBER	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
E-10	.0166	.0255	1000	5.08	4.678	6.97	1.37	30 - 40	.85
E-11	.0166	.0215	1000	4.28	4.627	6.42	1.5	25	.85
E-12	.0166	.035	1000	7.0	4.584	9.94	1.42	20 - 25	.85
E-13	.0166	.0515	1000	10.0	4.514	13.4	1.4	30	.85
E-14	.0166	.0195	300	1.16	4.874	1.74	1.5	80 - 100	.85
E-15	.0355	.061	116	3.02	4.835	3.49	1.16	100-110	.85

Series F

Objective: To cut with two heads; one in the front and the other in the back positioned in the same way.

Test Plan

To cut with the front head alone, then with the back head alone under the same conditions. Then cut with both heads engaged simultaneously. The cutting conditions will be repeats of some tests from Series B.

Note: The machine tool was adapted with some chip diverting devices.

The Tests Run

Due to the different conditions chosen for every test from F-1 to F-11, especially the kind and number of cutting heads engaged in every test, the detailed data sheets are given in Table 11. The results of the Series F tests are given in Table 12.

Remarks and Conclusions

The two heads were not aligned equally with respect to the workpiece due to the difference in their sizes. This usually resulted in unequal loads on both heads (i.e., unequal depths removed from both heads).

It was recommended that the next series be tried with the two heads staggered by a certain distance and one head will lead while the other will follow.

TABLE 11

SERIES F DATA SHEETS

ARMY PROJECT--Test Series F

No. of Heads 1 or 2 in front or in back **Cutting Disc** HSS

Material of Workpiece 4140 Rockwell C 30 **Position of Disc** .85

TEST	DEPTH (in.)	FEED (ipr)	DIA. (in.)	SPEED (sfpm)	HEAD	TIME (min.)	FINISH (RMS)	REMARKS
F-1	.020	.0166	4.412	300	front cutter	.41	100	The machine was adapted with a pan on the guide ways. 8" smooth cut; however, rough threaded surface.
F-2	.020	.0166	4.371	300	back cutter	.41	50	Long slightly curled chips through the tunnel. Finer finish on workpiece; no thread appears on surface.
F-3	.020	.0166	4.326	300	both	.41	110	Front cutter was not cutting--just small minute chips; however, very badly threaded surface was produced on workpiece. It was noticed that the back cutter was leading by 0.40 and maybe that is why it was the only cutter cutting.
F-4	.020 on back .040 on front	.0166	4.280	300	both	.41	160	Both cutters cutting same chip formation; however, front cutter produced heavier cross-section chip. The actual total depth was .054. Suggest repeat.
F-5	.020 on back .040 on front	.0166	4.172	300	both	.42	120	Workpiece is rugged; threaded chips from front cutter are heavier than back cutter.

TABLE 11 (Cont.)

ARMY PROJECT--Test Series F

No. of Heads 2 **Cutting Disc** HSS

Material of Workpiece 4140 Rockwell C 30 **Position of Disc** .85

TEST	DEPTH (in.)	FEED (ipr)	DIA. (in.)	SPEED (sfpm)	HEAD	TIME (min.)	FINISH (RMS)	REMARK
F-6	.020 back .040 front	.0166	4.713	300	both	.42	140	Threads disappeared on workpiece Actual depth was .030, with lead tool producing thinner chips
F-7	.020 both	.0166	4.606	300	2 heads cutting simultaneously	.41		The front cutter was the only one cutting effectively.
F-8	.020 both	.0166	4.565	300	"	.41	60	Very good finish on workpiece. Same chip cross-section from both.
F-9	.050 both	.0166	4.522	300	"	.41	85	Unequal chip cross section rugged heavy chips from front cutter. Smooth chips from back; finish is wavy
F-10	.025 both	.0166	4.418	1000	"	.13	80	Blue chips equal cross section from front and back. Very fine thread with smooth mirror-like finish
F-11	.025 both	.0355	4.374	300	"	.18	100	Chips from back are rugged; chips from front are smooth. Surface changed in appearance, became wavy at the end.

TABLE 12

SERIES F TEST RESULTS

TEST NUMBER	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
F-1	.0166	.0205	300	1.225	4.412	1.475	1.2	100	.85
F-2	.0166	.0225	300	1.34	4.371	1.475	1.1	50	.85
F-3	.0166	.023	300	1.37	4.326	1.88	1.37	110	.85
F-4	.0166	.054 .040/.054	300	3.23	4.280	3.62	1.12	160	.85
F-5	.0166	.029 .040/.020	300	1.73	4.172	3.21	1.85	120	.85
F-6	.0166	.030 .030/.020	300	1.79	4.713	2.41	1.34	120	.85
F-7	.0166	.0205 .020/.020	300	1.23	4.606	1.875	1.52	140	.85
F-8	.0166	.0215 .020/.020	300	1.284	4.565	1.875	1.46	60	.75/.85
F-9	.0166	.052 .050/.050	300	3.11	4.522	4.69	1.51	80-90	.75/.85
F-10	.0166	.022 .025/.025	1000	4.38	4.418	8.05	1.83	80	.75/.85
F-11	.0355	.0265 .025/.025	300	3.38	4.374	4.56	1.35	100	.75/.85

Series G

Objective: To test cutting with two heads; the front and the back staggered by a certain distance.

Test Plan

The experiment was set up so that the back head was leading by .042 in.; the front head was following.

Total depths of cut up to .075 in. split between the two cutters were tried as well as very fast speeds.

The detailed data sheet is given in Table 13. The results of the Series G tests are given in Table 14.

TABLE 13

SERIES G DATA SHEETS

ARMY PROJECT -- Test Series G

No. of Heads 2 **Cutting Disc** HSS

Material of Workpiece 4140 Rockwell C 30 **Position of Disc** .85

TEST	DEPTH (in.)	FEED (ipr)	DIA. (in.)	SPEED (sfpm)	HEAD	TIME (min.)	FINISH (RMS)	REMARKS Back cutter leads by .024" NO COOLANT
G-1	.025 on back .050 on front	.016	4.321	1000	both	.13	30	Front cutter-blue, thicker chips, back cutter-brown, thinner chips. Very shiny surface with fine serrations on it.
G-1.1	"	.016	4.228	1000	both	.13	30	Same chips as G-1; front cutter-blue wide; back cutter-purple, narrow. Smooth less shiny surface.
G-2	.0375 on back .075 on front	.0102	4.874	1000	both d = .075	.22	25	Front cutter-blue chips, wider; Back cutter-purple chips, narrow. Mirror-like finish.
G-3	.025 on back .050 on front	.0102	4.727	1330	both	.15	25-30	Front has wide chips; back has thinner chips. Fine finish. Feed did not stop automatically—back cutter hit the next boss, tool damaged.

TABLE 14

SERIES G TEST RESULTS

TEST NUMBER	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
G-1	.0166 .050/.025	.0415	1000	8.27	4.321	14.22	1.72	30	.85/.85
G-1.1	.0166 .050/.025	.050	1000	9.6	4.228	14.9	1.55	30	.85/.85
G-2	.0102 .075/0375	.073	1000	8.95	4.874	17.3	1.93	25-30	.85/.85
G-3	.0102 .050/.025	.049	1330	8.0	4.727	15.4	1.92	25-30	.85/.85

Series H

Objective: To cut with a single point tool in a holder fixed to the Bolster plate -- to compare the UHP and SF of the disc with the single point tool.

Test Plan

Two inserts were chosen for the tests; a Carboloy 350 SNG 432 for tests H-1 through H-4, and a ceramic Co6 for test H-5.

Tool cratered badly in test H-4 (failed).

The results of the Series H tests are given in Table 15.

TABLE 15

SERIES H TEST RESULTS

TEST NUMBER	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
H-1	.0102	.044	300	1.615	4.633	1.475	.915	95	
H-2	.0166	.044	500	4.38	4.545	3.76	.86	300	
H-3	.0166	.0195	1000	3.89	4.457	2.95	.758	200	
H-4	.0166	.0545	1000	10.85	4.418	11.5	1.06	220	
H-5	.0166	.0505	1000	10.05	4.309	8.32	.827	200	

Series I

Objective: Test runs on a carbide disc provided by the Adamas Carbide Corporation in one cutting head. To compare the performance of carbide with the high speed steel discs.

Constant Parameters:

a. One head with carbide disc

b. Workpiece: AISI 4140 Rockwell C 30

c. Cutter diameter: 2-1/2 in.

d. Cutter position: Y = .80 in.

e. Feed: .0116 ipr

f. No coolant

Independent Variables:

a. Speed: 300 - 500 - 1000 - 1000 SFPM

b. Depth: .035 - .050 - .035 - .050 in.

The detailed data sheet is given in Table 16. The results of the Series I tests are given in Table 17.

TABLE 16

SERIES I DATA SHEETS

ARMY PROJECT--Test Series I

No. of Heads 1 with carbide disc (front head) Cutting Disc Carbide disc

Material of Workpiece 4140 Rockwell C 30 Position of Disc Y = .80

TEST	DEPTH (in.)	FEED (ipr)	DIA. (in.)	SPEED (sfpm)	HEAD	TIME (min.)	FINISH (RMS)	REMARKS NO COOLANT
I-1	.035	.0166	4.874	300		.45	40	Smooth cut, smooth finish. Long, continous chip.
I-2	.050	.0166	4.806	500		.29	100	Non-smooth cut; vibration-serration of surface finish. Blue chips too much deformed. Cutter chipped--may be due to the tailstock being loose.
I-2.1	.050	.0166	4.706	500		.28	70	Smooth cut. Blue chips; however, cutter was chipped in another place, mainly due to dragging it backward on the workpiece. Chips were cut shorther due to hitting the crack in the cutter.
I-3	.035	.0166	4.608	1000		.10	50	Smooth cut, shiny surface finish. Short chips.
I-4	.050	.0166	4.541	1000		.12	40	Smooth cut, shiny finish. Blue chips broken due to the chipping in the cutter.

TABLE 17

SERIES I TEST RESULTS

TEST NUMBER	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
I-1	.0166	.034	300	2.03	4.874	3.88	1.91	40	.80
I-2	.0166	.050	500	4.97	4.806	8.04	1.61	100	.80
I-2.1	.0166	.049	500	4.87	4.706	7.57	1.56	70	.80
I-3	.0166	.0325	1000	6.47	4.608	11.4	1.76	50	.80
I-4	.0166	.050	1000	9.96	4.541	22.8	2.29	40	.80

Series J

Objective: To investigate vibration (displacement of several parts on the set-up) using a dial indicator and low speed.

Test J-1

The dial indicator checking the cutting head conditions:

a. Depth: .035 in.

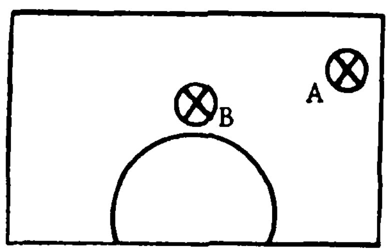
b. Feed: .0166 ipr

c. Speed: 35 SFPM

Note: The dial indicator did not show any displacement during cut. The cut was very smooth and finish was great.

Test J-2

The dial indicator checking the bolster plate:



At position A, there was no displacement; however, when dial was set at position B, it showed an appreciable displacement of .0015 in. which may indicate that the plate may not be stiff enough and needs to be reinforced.

The plate was stiffened by a heavy bar clamped to its back. Further dial indicator testing proved that the stability and stiffness of the whole set-up was satisfactory.

Note: A special test was conducted before Series K to evaluate the performance at relatively high MRR with very low speed using the carbide cutter. These conditions were:

a. Depth: .050 in.

b. Feed: .0666 ipr

c. Speed: 100 SFPM

The test failed -- the cutter broke into pieces.

Series K

Objective: To investigate different positioning of the one carbide cutter in the front head seeking an optimal positioning of the smaller diameter carbide cutter as compared to the 3" HSS cutter.

A new carbide cutter was set in its mandrel in the front head. The cutting conditions were set constant and the cutter positions were variable.

Constant Parameters:

a. Speed: 500 SFPM

b. Feed: .0166 ipr

c. Depth: .025 in.

Independent Variable:

Y = .6 -.9 in.

The results of this series showed that at Y = .7, the cutter performed the best from the point of view of smoothness of cut and surface finish on workpiece. However, a Y position of .6 resulted in lower UHP as shown in the result sheet.

The detailed data sheet is given in Table 18. The results of the Series K tests are given in Table 19.

TABLE 18

SERIES K DATA SHEETS

ARMY PROJECT--Test Series K

No. of Heads 1-the front head   **Cutting Disc** Carbide

Material of Workpiece 4140 Rockwell C 30   **Position of Disc** to be investigated

TEST	DEPTH (in.)	FEED (ipr)	DIA. (in.)	SPEED (sfpm)	CUTTER Position	TIME (min.)	FINISH (RMS)	REMARK
K-1	.025	.0166	4.883	500	.7	.28	30	Smooth cut, shiny finish. Long, blue chips. No coolant.
K-2	.025	.0166	4.846	500	.8	.29	45	Smooth cut, shiny finish. Long blue chips. No coolant.
K-3	.025	.0166	4.806	500	.9	.28	20-50 from one side to another	To much chattering; shiny surface with bumps.
K-4	.025	.0166	4.770	500	.6	.28	30	Very smooth cut, shiny surface. Brown chips, big curls.

TABLE 19

SERIES K TEST RESULTS

TEST	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
K-1	.0166	.0175	500	1.74	4.883	4.56	2.62	30	.70
K-2	.0166	.020	500	2.0	4.846	5.1	2.54	45	.80
K-3	.0166	.018	500		4.806			22-55	.90
K-4	.0166	.023	500	2.29	4.770	4.28	1.87	30	.60

Series L

Test Plan

No pre-set conditions were planned for this series -- the main objective was to try the machining operations with the cluster of three heads with HSS cutters on them. (The bottom cutter needed a different head base which was made, and the head was fastened to the bolster plate in the same position as the back head and front head.)

Note: The back head is labeled #1; the front head is labeled #2; the bottom head is labeled #3.

The data sheets and the result sheet show the progression of the cutting conditions and the number of heads engaged in every test.

The detailed data sheets are given in Table 20. The results of the Series L tests are given in Table 21.

TABLE 20

SERIES L DATA SHEETS

ARMY PROJECT--Test Series L

No. of Heads 3 **Cutting Disc** HSS

Material of Workpiece 4140 Rockwell C 30 **Position of Disc** .75

TEST	DEPTH (in.)	FEED (ipr)	DIA. (in.)	SPEED (sfpm)	HEAD	TIME (min.)	FINISH (RMS)	REMARK
L-1	.025	.0166	4.724	500	the bottom cluster alone		80	Smooth cut
L-2	.025 on each cutter total .075	.0166	4.666	500	all 3 cutters		70	Too much chatter; scars on surface of workpiece
L-3	.025 .050 .075	.0166	4.521	500	"	.25	50-100	The 3 heads are staggered; back is #1, front is #2, and bottom is #3. Pounding. Non-uniform serration on workpiece and chips are different.
L-4	.025 on back .050 on bottom	.0166	4.358	500	"	.25	70-120	Too much pounding; chips are unequal.
L-5	"	.0166	4.235	500	front and bottom cutters	.26		Some pounding. The bottom one only cut, the front made some very thin chips

TABLE 20 (Cont.)

ARMY PROJECT--Test Series L

No. of Heads 3 **Cutting Disc** HSS

Material of Workpiece 4140 Rockwell C 30 **Position of Disc** .75

TEST	DEPTH (in.)	FEED (ipr)	DIA. (in.)	SPEED (sfpm)	HEAD	TIME (min.)	FINISH (RMS)	REMARKS
L-6	.050	.0166	4.115	500	bottom only	.26		Pounding.
L-7	.050	.0166	4.880	500	"			New land. Still chattering; infer that bottom cutter chatters under heavy cut. No chips collected.
L-8	.0375 front .0125 bottom .050 total	.0166	4.763	500	front and bottom	.28	60-70	Set bottom cutter to finish only. Smooth cut, no chatter. Thick chip from front; thin chip from bottom.
L-9	.025 front .025 back .0125 bottom	.0166	4.655	500	3 heads	.28		3 heads with the bottom one cutting the least depth. Too much chatter no surface finish measurement, no chips collected.
L-10	.0375 back .0125 bottom	.0166	4.520	500	2 heads	.28		2 heads; back at .0375 and bottom at .0125. Too much chatter. Bottom cutter produced thicker, bluish chips.

TABLE 20 (Cont.)

ARMY PROJECT--Test Series L

No. of Heads 3 — Cutting Disc HSS

Material of Workpiece 4140 Rockwell C 30 — Position of Disc .75

TEST	DEPTH (in.)	FEED (ipr)	DIA. (in.)	SPEED (sfpm)	HEAD	TIME (min.)	FINISH (RMS)	REMARKS
L-11	.0125 bottom .0125 back .0375 front	.0166	4.406	500	3 heads	.24	100	Pounding and chattering. Three unequal chips· blue from bottom, rugged from the front, & smooth from the back. Chippings from bottom too.
L-12	.0125 each .0375 total	.0102	4.270	500	3 heads	.40		Reduced feed to .0102, equal depth on cutter. Pounding unequal chips: bottom one was making all the cuts; back cutter produced hair chippings; front cutter did not even rotate.
L-13	.0125 each .0375 total	.0102	4.187	500	3 at equal depth	.38		Chattering; however the three cutters produced equal thickness chips. The front and bottom produced their chips in clippings; the back produced longer chips.
L-14	.0125 bottom	.0102	4.101	500	bottom alone			

TABLE 21

SERIES L TEST RESULTS

TEST	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
L-1	.0166	.029	500	2.9	4.724	4.43	1.52	80	.75
L-2	.0166	.025 .050 .0725 .075	500	7.25	4.666	12.2	1.68	70	.75
L-3	.0166	.025 .050 .0815 .075	500	8.15	4.521	11.65	1.43	50-100	.75
L-4	.0166	.025 .0615 .050	500	6.15	4.358	11.0	1.79	70-120	.75
L-5	.0166	.025 .060 .050	500	6.0	4.235	8.31	1.38		.75
L-6	.0166	.050	500	6.75	4.115	7.22	1.07		.75
L-7	.0166	.050	500	5.85	4.880	8.17	1.40		.75
L-8	.0166	.0325 .054 .050	500	5.4	4.763	7.77	1.44		.75
L-9	.0166	.025 .025 .0675 .0125	500	6.75	4.655	11.5	1.71		.75

TABLE 21 (Cont.)

TEST	FEED ipr	DEPTH inches	SPEED sfpm	REMOVAL RATE in^3/min	DIA. OF WORK-PIECE	CUTTING HP	UHP $\left[\frac{HP}{in^3/min}\right]$	SURFACE FINISH	Y inches
L-10	.0166	.0375 .057 .050	500	5.7	4.520	8.17	1.43		.75
L-11	.0166	.0125 .050 .068 .0625	500	6.8	4.406	9.38	1.38		.75
L-12	.0102	.0125 .025 .0415 .0375	500	2.64	4.270	3.75	1.42		.75
L-13	.0102	.0125 .025 .043 .0375	500	2.63	4.187	4.02	1.53		.75

Series M

Objective: To further investigate the capability and limitations of machining with a cluster of three HSS cutter heads, realizing the shortcomings of the engine lathe and its carriage design when machining with cutters producing forces and stresses in non-conventional direction.

It was observed from the tests in Series L that the machining operation performed with the bottom and the back cutters engaged simultaneously in the cut always produced additional chatter and contributed to inefficient performance.

Test Plan

It was decided to machine with the bottom cutter alone to find out the extent of the safe cutting conditions before the damaging chatter occurs. Then, to run some tests with three cutters with the same objective.

Note: Test M-5 was run with the front and bottom cutters engaged only in the cut and produced the best results.

The detailed data sheet is given in Table 22.

TABLE 22

SERIES M DATA SHEET

ARMY PROJECT--Test Series M

No. of Heads 1 and 3 — Cutting Disc HSS

Material of Workpiece 4140 Rockwell C 30 — Position of Disc .80

TEST	DEPTH (in.)	FEED (ipr)	DIA. (in.)	SPEED (sfpm)	HEAD	TIME (min.)	FINISH (RMS)	REMARKS
M-1	.0125 acutal .019	.0102	4.880	300	bottom only	.71	90	Smooth cut. Serration on surface finish. Short chips (chips collected).
M-2	.0125 actual .0145	.0102	4.842	500	"	.45	80	Smooth cut. Finer serration on surface finish. Broken chips (chips collected).
M-3	.0125 actual .015	.0102	4.813	700	"	.32	75	Smooth cut. Some chattering by the end of the cut. Bluish, broken chips (chips collected).
M-4	.0125 each .0375 total .042 actual	.0102	4.783	300	3 heads equal depth	.73	130	Smooth cut. Serration on surface finish. Equal chips, except the chips from the bottom were rugged and battered.
M-5	.0125 each .0375 total .039 actual	.0102	4.698	500	2 heads equal depth	.44	60-80	BEST CUT--the smoothest cut ever; equal chips, no serration on workpiece. Fine finish. However, only the front and bottom cutters were set right to cut.
M-6	.0125 each .0375 total	.0102	4.620	500	3 heads equal depth	.44		Repeat and make sure that 3 heads are engaged. Cut was not smooth chattering bad finish.

Series N, O, P (Milling)

Table 3 summarizes the main features of this series of tests. Series N and O were low cutter velocity tests performed on the Monarch Lathe and Series P was a high cutter velocity test performed on the Pacemaker Lathe.

Figures 26 and 27 show a hydraulic motor (10 HP) added to power the cutting head used in tests A through M on the Monarch Lathe. The mandril had to be redesigned to hold the milling cutters. An assembly of the low cutter velocity milling setup is shown in Figure 28.

Test Series N was conducted with milling cutters having the following specifications: 60° single angle, right hand HSS, 2-1/2 x 1/2 x 7/8 in. The commercial cutters were reground to improve their cutting edge capability.

Test Series O was conducted with a carbide tipped milling cutter (shell mill, 4 teeth, 3/4" hole, 2" diameter). See Figure 29.

The milling cutters described above are shown in Figure 30.

Test Series P was conducted with the same carbide tipped milling cutter as Series O. This cutter was mounted on a different spindle head (see Figure 31) on the Pacemaker Lathe. It was powered by a 5 HP motor.

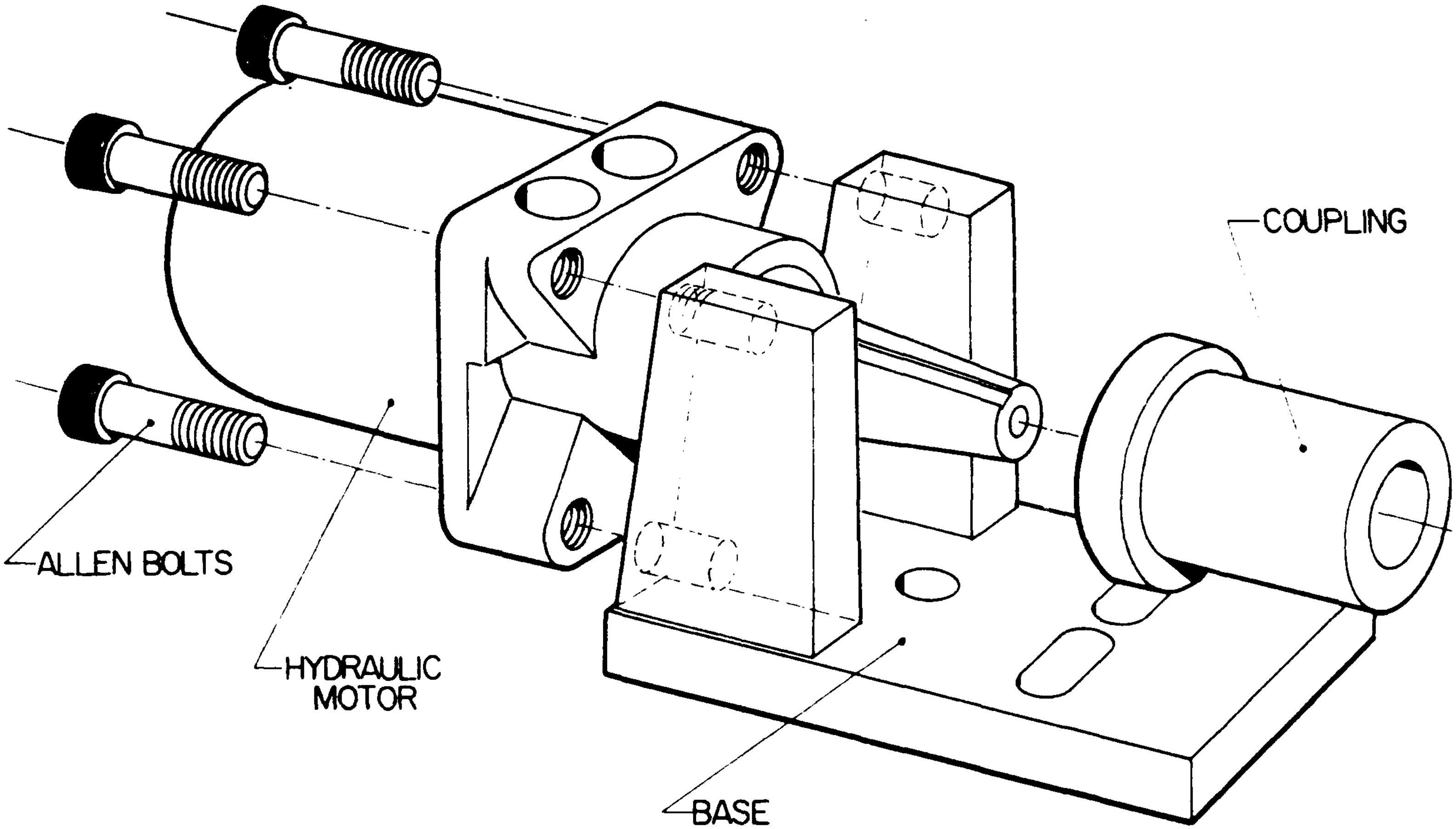


FIGURE 26. Hydraulic Motor Assembly

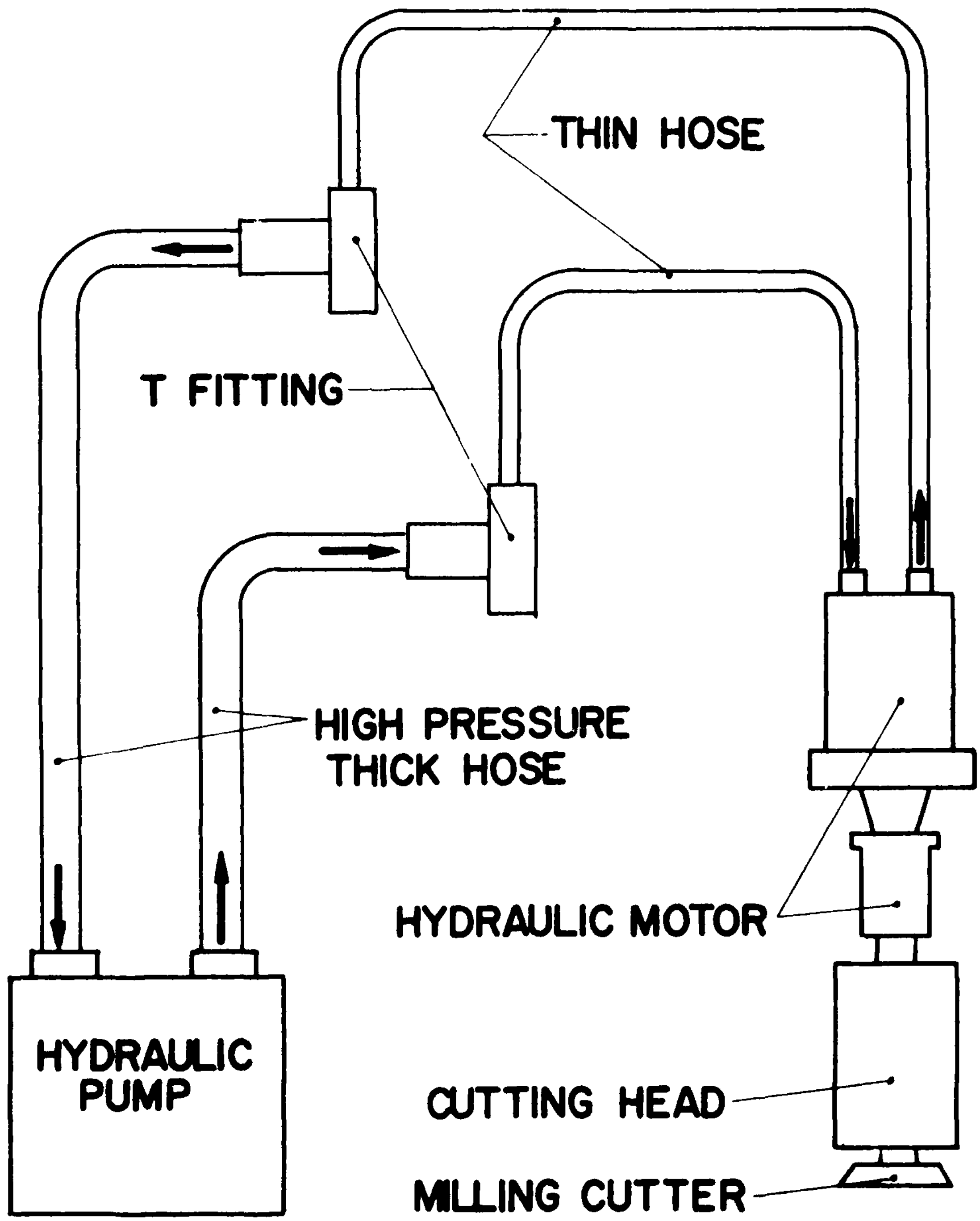


FIGURE 27. Schematic Assembly Milling Set Up

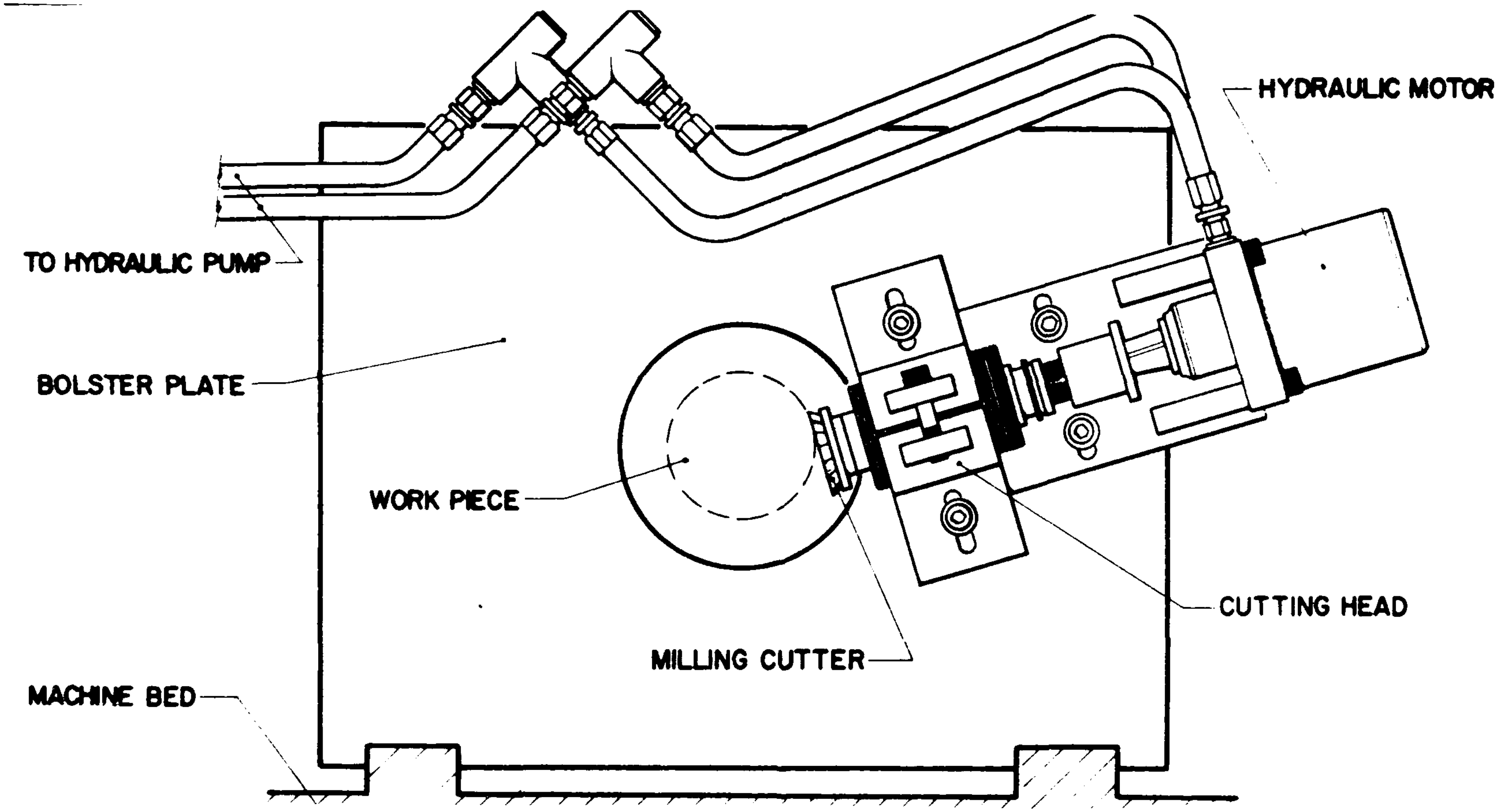


FIGURE 28. Milling - One Cutter Set Up

FIGURE 29. Milling - Carbide Cutter Position

FIGURE 30 Cutting Tools Used in Tests

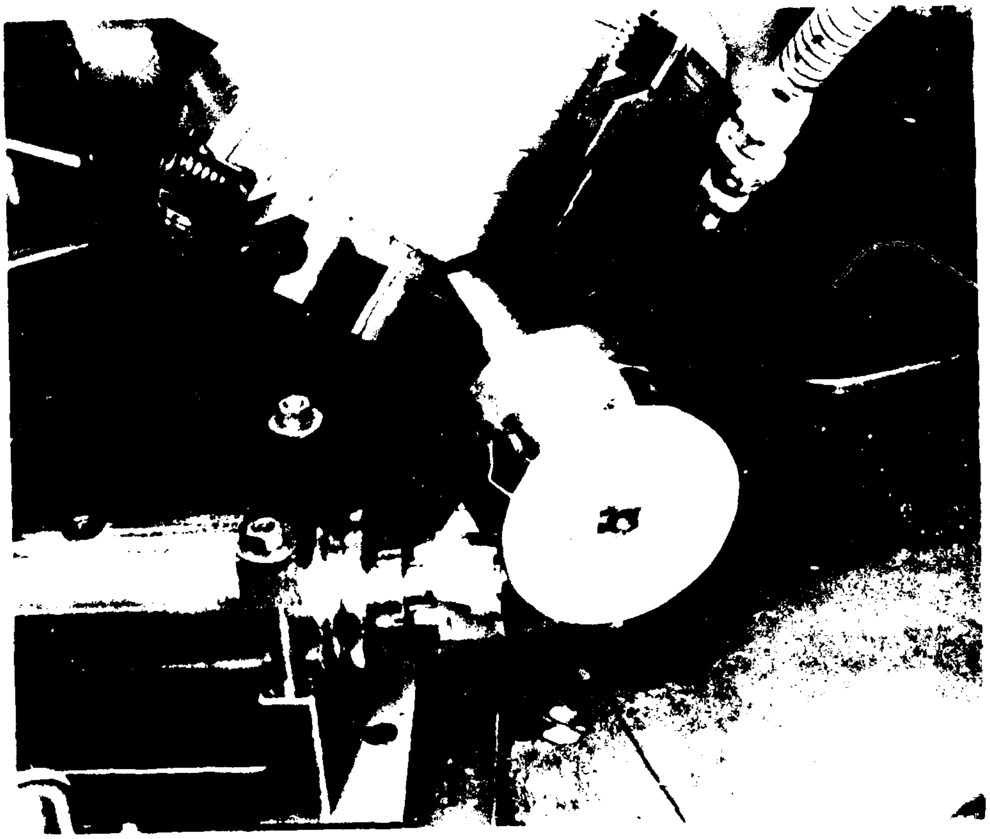


FIGURE 31.   Milling Test Carbide Cutter